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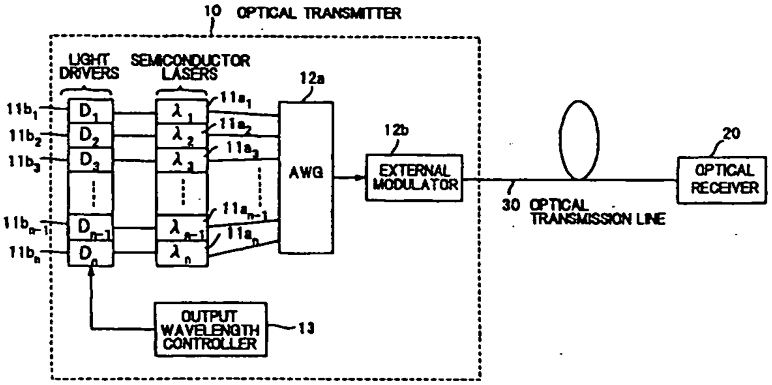
(54) Optical transmitter and optical transmission system

(57) An optical transmitter having a function which compensates for wavelength dispersion is provided with a plurality of light sources for outputting light having wavelengths that differ from one another. Before the optical transmission system begins operating, the wavelength of light output to an optical transmission line is varied by changing over the light sources in order to detect a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line. During system operation, the light having the detected optimum wavelength is output to the optical transmission line.

FIG.8


10 OPTICAL TRANSMITTER
LIGHT DRIVERS
SEMICONDUCTOR LASERS
11b$_1$
11b$_2$
11b$_3$
11b$_{n-1}$
11b$_n$
D$_1$
D$_2$
D$_3$
D$_{n-1}$
D$_n$
λ$_1$
λ$_2$
λ$_3$
λ$_{n-1}$
λ$_n$
11a$_1$
11a$_2$
11a$_3$
11a$_{n-1}$
11a$_n$
12a
AWG
12b
EXTERNAL MODULATOR
OUTPUT WAVELENGTH CONTROLLER
13
30 OPTICAL TRANSMISSION LINE
20
OPTICAL RECEIVER

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Description

BACKGROUND OF THE INVENTION

[0001] This invention relates to an optical transmitter and optical transmission system. More particularly, the invention relates to an optical transmitter and optical transmission system having a function which compensates for wavelength dispersion in order to realize larger capacity, higher speed and longer transmission distance.

[0002] Though 10-Gbps optical transmission systems are currently in practical use, there is growing demand for networks of greater capacity owing to a marked increase in utilization of networks in recent years. In particular, highly precise dispersion compensation is required at transmission speeds above 10 Gbps. This means that measuring the dispersion value of an optical transmission line accurately and then compensating for this value is essential. The present invention relates to monitoring of the dispersion value of an optical transmission line and to a technique for optimum compensation of dispersion.

[0003] Signal energy contains a variety of components (different frequency components and different mode components), and signal waveform distortion will occur at the receiving end unless signal propagation delay time is constant. The phenomenon which is the cause of this delay distortion is referred to as "dispersion" and decides the transmission capacity of an optical fiber. In order to realize a further increase in capacity, speed and transmission distance in an optical transmission system, there is need for a technique for measuring dispersion with high precision and for compensating for this dispersion.

[0004] In a 40-Gbps optical transmission system, wavelength dispersion is one factor that limits transmission distance. Dispersion tolerance declines at the square of the bit rate. At 40 Gbps, dispersion tolerance is 30 ps/nm, which is much lower in comparison with a dispersion tolerance of about 800 ps/nm at 10 Gbps. Fig. 74A illustrates the relationship between amount of dispersion compensation and power penalty based upon a transmission experiment using 40-Gbps OTDM (optical time division multiplexing), 1.3-µm zero-dispersion SMF (Single-Mode Fiber) having a length of 50 km. Fig. 74B shows the measurement system. The system shown in Fig. 74B includes an optical transmitter TX, a receiver RX, 1.3-µm zero-dispersion SMF having a length of 50 km, and -920-ps/nm fixed-dispersion compensated fiber CB.

[0005] Though 1.3-µm zero-dispersion SMF has been used for optical transmission lines, dispersion at high transmission speeds imposes limitations. In recent years, therefore, dispersion-shifted optical fiber for the purpose of reducing dispersion by shifting the zero-dispersion wavelength from 1.3 to 1.55 µm has been developed and laid. The wavelength of light output from the transmitter is 1.55 µm. As a consequence, 1.55-µm light is transmitted via the 1.3-µm zero-dispersion SMF laid originally.

[0006] When a 40-Gbps baseband signal is transmitted by a 1.55-µm optical signal via a 1.3-µm zero-dispersion SMF having a length of 50 km, dispersion of 920 ps/nm is produced. Accordingly, if 100% dispersion compensation is applied using the -920-ps/nm fixed-dispersion compensated fiber CB, reception sensitivity degradation will be 0 dB. However, if the amount of dispersion compensation is much larger or smaller than 100% dispersion compensation (= -920 ps/nm), reception sensitivity degradation rises and becomes 1 dB at amounts of dispersion compensation of -905 ps/nm and -935 ps/nm, as shown in Fig. 74A. In other words, if further dispersion in excess of ±15 ps/nm occurs at 100% dispersion compensation (amount of dispersion compensation = -920 ps/nm), reception sensitivity degradation will exceed 1 dB.

[0007] Accordingly, dispersion compensation tolerance when a power penalty of less than 1 dB is adopted as a condition for enabling transmission is a low 30 ps/nm, meaning that precise dispersion compensation must be carried out. Further, owing to temperature and stress which acts upon the optical fiber, the amount of change in transmission-line dispersion must be measured and the amount of dispersion compensation must be optimized within this narrow tolerance in conformity with change with the passage of time. Tolerance deviation D_T due to temperature is as follows assuming a transmission line of SMF having a length of 50 km and a temperature change of -50°C to +100°C:

$$\begin{aligned} D_T &= 0.03\ (\mathrm{nm/^\circ C}) \times 150\ (^\circ\mathrm{C}) \times 0.07\ (\mathrm{ps/nm^2/km}) \times 50\ (\mathrm{km}) \\ &= 15.8\ (\mathrm{ps/nm}) \end{aligned}$$

Thus there is the danger that the dispersion compensation tolerance of 30 ps/nm will not be met.

[0008] Fig. 75 is a characteristic diagram of wavelength dispersion, in which the wavelength (nm) of light output from an optical transmitter is plotted along the horizontal axis and amount of wavelength dispersion is plotted along the vertical axis. When a 40-Gbps baseband signal is transmitted by a 1.55-µm optical signal via a 1.3-µm zero-dispersion SMF, dispersion of 920 ps/nm is produced, as mentioned above. Accordingly, if 100% dispersion compensation is applied using the -920-ps/nm fixed-dispersion compensated fiber CB, wavelength dispersion becomes zero at 1.552 µm. The zero-dispersion wavelength is 1.552 µm (= 1552 nm). If the wavelength of light output by the optical transmitter deviates from the zero-dispersion wavelength, wavelength dispersion of an amount indicated by the straight line in Fig. 75 is produced.

[0009] A method using 40-GHz component intensity in the baseband spectrum of an OTDM signal and NRZ signal has been considered as a method of wavelength dispersion compensation. This method utilizes a characteristic in which the amount of dispersion becomes zero and the eye pattern openness is maximized at a minimum point between two peaks of the 40-GHz component intensity.

[0010] Figs. 76A and 76B illustrate the results of simulations of 40-GHz component intensity and eye openness with respect to amount of dispersion in case of a 40-Gbps NRZ signal, in which dispersion value (ps/nm) is plotted along the horizontal axis and 40-Gbps component intensity and eye openness are plotted along the vertical axis. Fig. 76A is for a case where $\alpha > 0$ holds and Fig. 76B for a case where $\alpha < 0$ holds, where α is a chirp parameter representing direction (positive-or negative-going) and amount of fluctuation in a transmission waveform. Wavelength fluctuation (chirp) occurs when the voltage applied to an optical modulator increases or decreases owing to a rise and fall in a data pulse. Owing to the effects of chirping, (1) the rising edge of a pulse on the receiving side is delayed and the falling edge of the pulse is advanced ($\alpha < 0$), or (2) the rising edge of a pulse on the receiving side is advanced and the falling edge of the pulse is delayed ($\alpha > 0$). The diameter of the eye opening is reduced by being shrunk along the time axis in the case of the former and is reduced by being stretched along the time axis in the case of the latter.

[0011] In accordance with Figs. 76A and 76B, when $\alpha = +0.7, -0.7$ holds, the 40-GHz component intensity peaks where the value of dispersion is in the vicinity of -40 ps/nm and +40 ps/nm, respectively, and the minimum value is obtained at the foot of the peak. Here the dispersion value is zero and the eye openness is maximum. The reason why the 40-GHz component intensity becomes zero when the dispersion value is zero (zero-dispersion wavelength ≈ 1552 μm) and the eye openness is maximum is that in the case of the NRZ signal, 40 Gbps corresponds to 20 GHz and no 40-GHz component is included. This means that the zero-dispersion wavelength can be detected by detecting the foot of the 40-GHz component intensity.

[0012] Figs. 77A and 77B illustrate the temperature characteristic (experimental values) of wavelength vs. 40-GHz component intensity in the case of the 40-Gbps NRZ signal. These are the results of transmission experiments at temperatures of -35 to +65°C using a DSF having a length of 100 km, in which Fig. 77A is for a case where $\alpha > 0$ holds and Fig. 77B for a case where $\alpha < 0$ holds. As in the simulation results of Figs. 76A and 76B, the minimum-value point at the foot of the peak of the 40-GHz component intensity in each Figure indicates the zero-dispersion wavelength (amount of dispersion = 0) at plus and minus values of α. It will be understood that the zero-dispersion wavelength changes while following up a fluctuation in temperature. More specifically, when the amount of dispersion of the optical transmission line fluctuates owing to a change in temperature, the zero-dispersion wavelength of the optical transmission line increases or decreases correspondingly.

[0013] Accordingly, it will suffice to detect the zero-dispersion wavelength and make the wavelength of light output to the optical transmission line equal to this zero-dispersion wavelength on the sending side. However, since the zero-dispersion wavelength must be detected, it is necessary for the wavelength of light to be varied continuously over a wide range. The state of the art is such that a tunable laser in which wavelength can be varied continuously over a wide range is difficult or impossible to realize because of structural complications and for reasons of cost.

[0014] Utilizing a semiconductor array laser (in which a number of laser-diode chips are formed on a single wafer) currently undergoing research or a plurality of discrete semiconductor lasers used in existing optical systems is believed to be closer to actualization. However, in the case of a semiconductor array laser obtained by forming a number of laser-diode chips of different wavelengths on one wafer or a plurality of discrete semiconductor lasers having different wavelengths, light is interrupted when wavelength is switched and, as a result, interruption of the transmitted signal occurs. In addition, a large difference in signal delay time before and after wavelength switching is produced and signal degradation occurs.

SUMMARY OF THE INVENTION

[0015] Accordingly, an object of the present invention is to compensate for wavelength dispersion in an optical transmission line by outputting, to this optical transmission line, light having a wavelength for which the transmission characteristic is optimum for this wavelength dispersion, this being accomplished even if a tunable laser is not used.

[0016] Another object of the present invention is to so arrange it that neither signal interruption nor signal degradation occurs at the time of wavelength changeover even if a plurality of light sources having different wavelengths are used, as when use is made of a semiconductor array laser or a plurality of discrete semiconductor lasers.

[0017] A further object of the present invention is to so arrange it that wavelength can be switched in a simple manner using an arrayed waveguide grating (AWG), a star coupler, a variable-wavelength filter or a light attenuator.

[0018] Still another object of the present invention is to so arrange it that dispersion compensation can be carried out accurately by detecting zero-dispersion wavelength even in a case where a plurality of light sources having different wavelengths are used.

[0019] Still another object of the present invention is to so arrange it that signal degradation is prevented by eliminating or reducing signal delay before and after wavelength changeover even in a case where a plurality of light sources having different wavelengths are used.

[0020] Still another object of the present invention is to compensate for wavelength dispersion in an optical transmission line by multiplexing monitoring light with main-signal light, detecting whether zero-dispersion wavelength has shifted in the direction of long wavelength or short wavelength and whether zero-dispersion wavelength has become an intermediate wavelength between wavelengths of neighboring light sources, and changing over light sources when zero-dispersion wavelength becomes an intermediate wavelength between wavelengths of neighboring light sources.

[0021] Yet another object of the present invention is to improve detection precision of, e.g., the direction of fluctuation of zero-dispersion wavelength by making the polarization of main-signal light orthogonal to the polarization of monitoring light in a case where monitoring light is multiplexed with main-signal light and then transmitted.

[0022] A further object of the present invention is to make it possible to support any optical modulation scheme, such as NRZ modulation, RZ modulation and OTDM modulation.

[0023] Yet another object of the present invention is to compensate for wavelength dispersion of an optical transmission line by multiplexing main-signal light and two monitoring light beams, in which the wavelengths of the main-signal light and monitoring light are different from each other, and changing over the main-signal light when the zero-dispersion wavelength fluctuates and the intensity ratio of two wavelengths between which the zero-dispersion wavelength is sandwiched attains a predetermined value.

[0024] Yet another object of the present invention is to so arrange it that wavelength dispersion compensation can be applied to a wavelength multiplexing optical transmission system.

[0025] In accordance with the present invention, the foregoing objects are attained by providing an optical transmitter having a wavelength dispersion compensating function, comprising: a plurality of light sources for outputting light having wavelengths that differ from one another; and means for outputting, to an optical transmission line, light of a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line, the output light being obtained from light output by the plurality of light sources.

[0026] Further, in accordance with the present invention, the foregoing object is attained by providing an optical transmitter having a wavelength dispersion compensating function, comprising: a plurality of light sources for outputting light having wavelengths that differ from one another; means for outputting, to an optical transmission line, light of a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line, the output light being obtained from light output by the plurality of light sources; and means for changing over the light generated by the light sources and outputting this light to the optical transmission line, thereby changing the wavelength of light output to the optical transmission line; wherein the wavelength of light output to the optical transmission line is changed, before start of operation of an optical transmission system, in order to detect a wavelength whose transmission characteristic is optimum with regard to the wavelength dispersion exhibited by this optical transmission line, and the light having the detected optimum wavelength is output to the optical transmission line during system operation.

[0027] Further, in accordance with the present invention, the foregoing object is attained by providing an optical transmitter having a wavelength dispersion compensating function, comprising: a plurality of light sources for outputting light having wavelengths that differ from one another; means for outputting, to an optical transmission line, light of a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line, the output light being obtained from light output by the plurality of light sources; and means for causing fluctuation of the wavelength of the light output to the optical transmission line in order to detect a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line; wherein the light having the detected optimum wavelength is output to the optical transmission line during operation of an optical transmission system.

[0028] Further, in accordance with the present invention, the foregoing object is attained by providing an optical transmitter having a wavelength dispersion compensating function, comprising: a plurality of light sources for outputting light having wavelengths that differ from one another; means for outputting, as main-signal light to an optical transmission line, light of a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line, the output light being obtained from light output by the plurality of light sources; and means for multiplexing, with the main-signal light, monitoring light for detecting a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line; wherein the monitoring light is multiplexed with the main-signal light during operation of an optical transmission system and the light having the detected optimum wavelength is output to the optical transmission line as the main-signal light.

[0029] Other features and advantages of the present invention will be apparent from the following description taken in conjunction with the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0030]

Fig. 1 is a diagram useful in describing an overview of a first aspect of the present invention;
Fig. 2 is a diagram useful in describing an overview of a second aspect of the present invention;
Fig. 3 is a diagram useful in describing an overview of a third aspect of the present invention;
Fig. 4 is a graph showing the relationship between wavelength and delay time;
Figs. 5A and 5B are diagrams useful in describing methods of switching among light sources;
Fig. 6 is a diagram useful in describing a method of controlling laser injection current when switching among light-source wavelengths;
Fig. 7 is a graph showing the relationship between maximum wavelength spacing of light sources and dispersion compensation precision;
Fig. 8 is a diagram illustrating a first example of the construction of an optical transmitter having a plurality of light sources (in which semiconductor lasers are provided as the light sources and an arrayed waveguide grating is used for multiplexing light);
Fig. 9 is a diagram illustrating a second example of the construction of an optical transmitter having a plurality of light sources (in which semiconductor lasers are provided as the light sources and a star coupler is used for multiplexing light);
Figs. 10A and 10B are diagrams illustrating a third example of the construction of an optical transmitter having a plurality of light sources (in which semiconductor lasers are provided as the light sources and MI-DFB-LD-type lasers are used in modulators);
Fig. 11 is a diagram illustrating a fourth example of the construction of an optical transmitter having a plurality of light sources (in which a semiconductor array laser is provided as the light sources and an arrayed waveguide grating is used for multiplexing light);
Fig. 12 is a diagram illustrating a fourth example of the construction of an optical transmitter having a plurality of light sources (in which a semiconductor array laser is provided as the light sources and a star coupler is used for multiplexing light);
Fig. 13 is a diagram illustrating an embodiment in which dispersion compensation is performed in a case where optimum wavelength is already known;
Fig. 14 is a diagram illustrating a modification (multiple-repeater transmission) of an embodiment in which dispersion compensation is performed in a case where optimum wavelength is already known;
Fig. 15 is a diagram illustrating an embodiment in which dispersion compensation is performed in a case where optimum wavelength is not already known;
Fig. 16 is a diagram showing the feedback arrangement of a dispersion monitoring signal;
Fig. 17 is a diagram illustrating a modification (in which the transmission line is an SMF) for performing dispersion compensation in a case where a change in wavelength is small when optimum wavelength is unknown;
Fig. 18 is a diagram illustrating another embodiment (using light attenuators) for performing dispersion compensation in a case where a change in wavelength is small when optimum wavelength is unknown;
Fig. 19 is a diagram illustrating another embodiment (using a variable-wavelength filter) for performing dispersion compensation in a case where a change in wavelength is small when optimum wavelength is unknown;
Fig. 20 is a diagram showing the construction of the variable-wavelength filter;
Fig. 21 is a diagram showing the tuning characteristic of the variable-wavelength filter;
Fig. 22 is a diagram illustrating an embodiment (fluctuating wavelength) for performing dispersion compensation in a case where a change in wavelength is large when optimum wavelength is unknown;
Fig. 23 is a circuit diagram of an ATC circuit;
Fig. 24 is a graph showing the relationship between wavelength and monitoring component intensity;
Fig. 25 is a diagram illustrating an embodiment (with fluctuating wavelength and using a light attenuator) for performing dispersion compensation in a case where a change in wavelength is large when optimum wavelength is unknown;
Fig. 26 is a diagram illustrating an embodiment (with fluctuating wavelength and using a variable-wavelength filter) for performing dispersion compensation in a case where a change in wavelength is large when optimum wavelength is unknown;
Figs. 27A and 27B are diagrams useful in describing the principle of detection of, e.g., the direction in which a zero-dispersion wavelength fluctuates;
Fig. 28 is a diagram illustrating an embodiment (using monitoring light) for performing dispersion compensation in a case where a change in wavelength is large when optimum wavelength is unknown;
Fig. 29 is a flowchart of processing for wavelength-dispersion compensation at the time of system operation;

Fig. 30 is a diagram useful in describing control for switching wavelength to the long-wavelength side;

Fig. 31 is a diagram useful in describing control for switching wavelength to the short-wavelength side;

Fig. 32 is a diagram useful in describing range of filtering width;

Figs. 33A and 33B are diagrams useful in describing wavelength relationship between monitoring light and main-signal light;

Fig. 34 is a diagram showing an embodiment using a wavelength-dispersion monitor for calculating amount of wavelength dispersion from a pulse interval;

Figs. 35A, 35B and 35C are diagrams useful in describing the principle for calculating amount of wavelength dispersion;

Fig. 36 is a diagram showing an embodiment using a wavelength-dispersion monitor for calculating amount of wavelength dispersion from a pulse interval;

Fig. 37 is a diagram illustrating an embodiment (using monitoring light and light attenuators) for performing dispersion compensation in a case where a change in wavelength is large when optimum wavelength is unknown;

Fig. 38 is a diagram illustrating an embodiment (using monitoring light and a variable-wavelength filters) for performing dispersion compensation in a case where a change in wavelength is large when optimum wavelength is unknown;

Fig. 39 is a diagram showing an embodiment in which main-signal light and monitoring light are rendered orthogonal;

Figs. 40A, 40B and 40C are diagrams useful in describing detection of wavelength changeover point;

Fig. 41 is a diagram showing the configuration of an optical transmission system;

Fig. 42 shows the flow of processing for wavelength dispersion compensation (initial setting);

Figs. 43A, 43B, 43C and 43D are diagrams useful in describing dispersion compensation processing in a case where zero-dispersion wavelength moves toward the long-wavelength side;

Fig. 44 shows the flow of processing for wavelength dispersion compensation in a case where zero-dispersion wavelength moves toward the long-wavelength side (where changeover of monitoring light and changeover of main wavelength are indicated);

Fig. 45 shows the flow of processing for wavelength dispersion compensation in a case where zero-dispersion wavelength moves toward the long-wavelength side (control of main-wavelength changeover);

Fig. 46 is a diagram useful in describing control of changeover of main-signal light;

Figs. 47A, 47B and 47C show the results of experimentation in a case where two waves are used in detection of optimum wavelength;

Fig. 48 shows the flow of processing for wavelength dispersion compensation in a case where zero-dispersion wavelength moves toward the short-wavelength side (where changeover of monitoring light and changeover of main wavelength are indicated);

Figs. 49A, 49B, 49C and 49D are diagrams useful in describing a case where zero-dispersion wavelength moves toward the short-wavelength side;

Fig. 50 shows the flow of processing for wavelength dispersion compensation in a case where zero-dispersion wavelength moves toward the short-wavelength side (control of main-wavelength changeover);

Fig. 51 is a diagram useful in describing control of changeover of main-signal light;

Figs. 52A and 52B are diagrams of component intensity characteristics for respective types of modulation;

Fig. 53 is a diagram useful in describing an embodiment in which main-signal light is controlled in such a manner that the intensity of a specific frequency component takes on the maximum value;

Figs. 54A to 54F are diagrams useful in describing direction of fluctuation of wavelength for which intensity is maximum;

Fig. 55 is a diagram useful in describing fundamentals in a case where use is made of two wavelengths employing the peak of an intensity component;

Fig. 56 is a diagram showing the configuration of an optical transmission system in which changeover of main-signal light is controlled upon detecting a wavelength of for which intensity is maximum;

Fig. 57 is a diagram showing a modification of the optical transmission system in which changeover of main-signal light is controlled upon detecting a wavelength of for which intensity is maximum;

Fig. 58 is a diagram useful in describing a case where a wavelength for which the intensity of a specific frequency component indicates the minimum value is detected and main-signal light for which the intensity of a specific frequency component is maximized is sent to an optical transmission line;

Figs. 59A, 59B, 59C and 59D are diagrams useful in describing a case where three waves are used in detection of optimum wavelength;

Fig. 60 is a diagram showing the configuration of an optical transmission system in which wavelength dispersion is compensated for using three waves, namely main-signal light and two monitoring light beams;

Fig. 61 shows the flow of processing for wavelength dispersion compensation in a case where three waves are used (initial setting);

Fig. 62 shows the flow of processing for wavelength dispersion compensation in a case where three waves are used (where changeover of monitoring light and changeover of main wavelength are indicated);

Fig. 63 shows the flow of processing for wavelength dispersion compensation in a case where three waves are used (control of main-wavelength changeover);

Fig. 64 is a diagram useful in describing control of changeover of main-signal light;

Fig. 65 is a diagram showing the configuration of a wavelength multiplexing optical transmission system (n-wavelength multiplexing);

Figs. 66A, 66B and 66C are diagrams useful in describing a case where wavelength multiplexing is performed, in which Fig. 66A illustrates an initial state, Fig. 66B a case where optimum wavelength has been moved toward the side of shorter wavelength, and Fig. 66C a case where optimum wavelength has been moved toward the side of longer wavelength;

Fig. 67 is a diagram showing a system configuration when four waves are multiplexed;

Fig. 68 is a diagram useful in describing a case where four waves are multiplexed;

Fig. 69 is a diagram showing a system configuration when four waves are multiplexed;

Fig. 70 is a diagram showing a system configuration when four waves are multiplexed;

Fig. 71 is a diagram for describing four-wave multiplexing;

Fig. 72 is a diagram showing the configuration of wavelength multiplexing in a case where variable-wavelength light sources are used;

Fig. 73 is a diagram showing the modification of wavelength multiplexing in a case where variable-wavelength light sources are used;

Figs. 74A and 74B are diagrams useful in describing the relationship between amount of dispersion compensation and power penalty, as well as a measurement system, based upon a transmission experiment using 40-Gbps OTDM (optical time division multiplexing), 1.3-μm zero-dispersion SMF having a length of 50 km;

Fig. 75 is a characteristic diagram of wavelength dispersion;

Figs. 76A and 76B illustrate the results of simulations of 40-GHz component intensity and eye openness in case of an NRZ signal; and

Figs. 77A and 77B illustrate the temperature characteristic (experimental values) of wavelength vs. 40-GHz component intensity in the case of the 40-Gbps NRZ signal.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

(A) Overview of the present invention

(a) Construction

[0031] Figs. 1 to 3 are diagrams useful in describing an overview of first to third aspects of the present invention.

[0032] Shown in Figs. 1 to 3 are an optical transmitter 10, an optical receiver 20, an optical transmission line 30, an optimum-wavelength detector (dispersion monitor) 40 for detecting a wavelength (zero-dispersion wavelength) whose transmission characteristic is optimum in regard to wavelength dispersion of the optical transmission line, and an optical transmission line 50 for sending the result of detection to the optical transmitter 10. If the wavelength of light output to the optical transmission line is the zero-dispersion wavelength, the optimum-wavelength detector 40 utilizes the fact that the intensity of a specific frequency component in a received baseband spectrum signal will have the minimum value.

[0033] The optical transmitter 10 includes a plurality of light sources 11_1 - 11_n having different wavelengths (λ_1 - λ_n) and formed by a semiconductor array laser or a plurality of discrete semiconductor lasers; an optical output unit 12 for outputting a prescribed light beam, from among the light beams generated by the plurality of light sources, to the optical transmission line 30; and an output wavelength controller 13a for varying the wavelength of the light output to the optical transmission line 30 and for outputting light of the optimum wavelength to the optical transmission line based upon the detection made by the optimum-wavelength detector 40. In the explanatory view of Fig. 2, the optical transmitter 10 further includes a wavelength controller 13b for minutely changing, at a prescribed frequency, the wavelength of the light output to the optical transmission line. In the explanatory view of Fig. 3, the optical transmitter 10 further includes, instead of the wavelength controller 13b, a monitoring-light multiplexing controller 13c for multiplexing monitoring light with main-signal light.

(b) Overview of first aspect (Fig. 1)

[0034] The plurality of light sources 11_1 - 11_n for generating light having different wavelengths λ_1 - λ_n are provided. If the wavelength (the zero-dispersion wavelength) that will have the optimum transmission characteristic in regard to wavelength dispersion exhibited by the optical transmission line is already known, the optical output unit 12, under the control of the output wavelength controller 13a, outputs to the optical transmission line 30 the light beam whose wavelength is closest to the optimum wavelength among the light beams produced by the plurality of light sources. If the optimum wavelength is not known, then, before the optical transmission system starts operating, the optical output unit 12, under the control of the output wavelength controller 13a, changes the wavelength of light by successively outputting to the optical transmission line 30 prescribed light beams from among the light beams produced by the plurality of light sources, and the optimum-wavelength detector 40 notifies the output wavelength controller 13a in optical transmitter 10 of the timing at which the intensity of a specific frequency component in a received baseband spectrum signal is minimized. The output wavelength controller 13a recognizes the zero-dispersion wavelength from the wavelength of the light that was being output to the optical transmission line at the above-mentioned timing, i.e., when the intensity of the specific frequency component attained the minimum value. When the system is operating, the optical output unit 12, under the control of the output wavelength controller 13a outputs to the optical transmission line 30 light having the wavelength nearest to the optimum wavelength (the zero-dispersion wavelength) detected by the optimum-wavelength detector 40 among the light beams output by the plurality of light sources 11_1 - 11_n.

[0035] In accordance with the principles of the first aspect of the invention, wavelength dispersion exhibited by an optical transmission line is compensated for by outputting, to this optical transmission line, light having a wavelength for which the transmission characteristic is optimum for this wavelength dispersion, this being accomplished without using a tunable laser.

(c) Overview of second aspect (Fig. 2)

[0036] The plurality of light sources 11_1 - 11_n for generating light having different wavelengths λ_1 - λ_n are provided. Before the optical transmission system starts operating, the optical output unit 12, under the control of the output wavelength controller 13a, changes the wavelength of light by successively outputting to the optical transmission line 30 prescribed light beams from among the light beams produced by the plurality of light sources, and the optimum-wavelength detector 40 detects the timing at which the intensity of a specific frequency component in a received baseband spectrum signal is minimized and notifies the output wavelength controller 13a in optical transmitter 10 of this timing. The output wavelength controller 13a recognizes the zero-dispersion wavelength from the wavelength of the light that was being output to the optical transmission line at the above-mentioned timing, i.e., when the intensity of the specific frequency component attained the minimum value. When the system is operating, the optical output unit 12, under the control of the output wavelength controller 13a, outputs to the optical transmission line 30 light having the wavelength nearest to the optimum wavelength detected by the optimum-wavelength detector 40 among the light beams output by the plurality of light sources 11_1 - 11_n, and the wavelength controller 13b causes the wavelength of the light output to the optical transmission line to fluctuate minutely at a predetermined low frequency.

[0037] During system operation also the optimum-wavelength detector 40 controls the detection of optimum wavelength and notifies the output wavelength controller 13a in optical transmitter 10 of the timing at which the intensity of the specific frequency component is minimized. The output wavelength controller 13a recognizes the zero-dispersion wavelength from the wavelength of the light that was being output to the optical transmission line at the above-mentioned timing, i.e., when the intensity of the specific frequency component attained the minimum value. If the zero-dispersion wavelength varies owing to aging or the like and becomes a wavelength intermediate the wavelength of the present light source and the wavelength of the neighboring light source, the optical output unit 12 changes over the light output to the optical transmission line 30 from the light of the present light source to the light of the neighboring light source in response to control performed by the output wavelength controller 13a. Control for wavelength-dispersion compensation is thenceforth performed in similar fashion.

[0038] Thus, even if a plurality of light sources having different wavelengths are used, dispersion can be compensated for accurately by detecting the zero-dispersion wavelength before and during system operation.

[0039] Further, when the zero-dispersion wavelength has shifted to a wavelength intermediate the wavelength of the present light source and the wavelength of the neighboring light source, the light output to the optical transmission line is switched from the light of the present light source to the light of the neighboring light source. As a result, it is possible to eliminate or reduce signal delay before and after wavelength switching, thereby preventing signal degradation.

[0040] Further, when light sources are changed over, wavelength can be changed over without instantaneous interruption of light by gradually reducing the amount of current injected into the present light source and gradually increasing the amount of current injected into the neighboring light source. Similarly, when light sources are changed over, wavelength can be changed over without instantaneous interruption of light and signal interruption can be prevented by outputting light from the present light source and light from the neighboring light source to the optical transmission line simultaneously and then halting the output of light to the optical transmission line from the present light source.

(d) Overview of third aspect (Fig. 3)

[0041] The plurality of light sources 11_1 - 11_n for generating light having different wavelengths λ_1 - λ_n are provided. Before the optical transmission system starts operating, the optical output unit 12, under the control of the output wavelength controller 13a, changes the wavelength of light by successively outputting to the optical transmission line 30 prescribed light beams from among the light beams produced by the plurality of light sources, and the optimum-wavelength detector 40 detects the timing at which the intensity of a specific frequency component in a received baseband spectrum signal is minimized and notifies the output wavelength controller 13a in optical transmitter 10 of this timing. The output wavelength controller 13a recognizes the zero-dispersion wavelength from the wavelength of the light that was being output to the optical transmission line at the above-mentioned timing, i.e., when the intensity of the specific frequency component attained the minimum value. When the system is operating, the optical output unit 12, under the control of the output wavelength controller 13a, outputs to the optical transmission line 30 light, which serves as main-signal light, having the wavelength nearest to the optimum wavelength detected by the optimum-wavelength detector 40 among the light beams output by the plurality of light sources 11_1 - 11_n. The optical output unit 12, under the control of the monitoring-light combination controller 13c in this case, combines monitoring light with the main-signal light and outputs the result to the optical transmission line. By way of example, the monitoring light is light output from a light source neighboring the present light source.

[0042] During system operation also the optimum-wavelength detector 40 controls the detection of optimum wavelength, detects (1) the direction in which the zero-dispersion wavelength fluctuates and (2) the fact that the zero-dispersion wavelength has shifted to a wavelength intermediate the wavelength of the main-signal light and the wavelength of the neighboring light source, these being detected from the intensity of a specific frequency component in a baseband spectrum signal of the received main-signal light and the intensity of a specific frequency component in a baseband spectrum signal of monitoring light, and notifies the output wavelength controller 13a in the optical transmitter 10 of the result of detected. As a result, the optical output unit 12, in response to control by the output wavelength controller 13a, switches the light output to the optical transmission line 30 from the light of the present light source to the light of the neighboring light source. Control for wavelength-dispersion compensation is thenceforth performed in similar fashion.

[0043] Thus, wavelength dispersion of the optical transmission line can be compensated for accurately by combining monitoring light with main-signal light, detecting whether the zero-dispersion wavelength has fluctuated in the direction of longer wavelength or shorter wavelength and whether the zero-dispersion wavelength has become a wavelength intermediate the wavelengths of the neighboring light sources, and changing over the light source when the zero-dispersion wavelength has become a wavelength intermediate the wavelengths of the neighboring light sources.

[0044] Further, when the zero-dispersion wavelength has shifted to a wavelength intermediate the wavelength of the present light source and the wavelength of the neighboring light source, the light output to the optical transmission line is switched from the light of the present light source to the light of the neighboring light source. As a result, it is possible to eliminate or reduce signal delay before and after wavelength switching, thereby preventing signal degradation.

[0045] Further, when light sources are changed over, wavelength can be changed over without instantaneous interruption of light by gradually reducing the amount of current injected into the present light source and gradually increasing the amount of current injected into the neighboring light source. Similarly, when light sources are changed over, wavelength can be changed over without instantaneous interruption of light and signal interruption can be prevented by outputting light from the present light source and light from the neighboring light source to the optical transmission line simultaneously and then halting the output of light to the optical transmission line from the present light source.

[0046] Further, by making the polarization of main-signal light orthogonal to the polarization of monitoring light and sending the main-signal light and monitoring light to the optical transmission line while maintaining this state of orthogonal polarization, it is possible to prevent beats produced between signals of neighboring wavelengths and to improve detection accuracy in the optimum-wavelength detector.

[0047] Further, two waves of monitoring light are used, the intensities of specific frequency components contained in the main-signal light and in these two waves of monitoring light are compared to thereby detect a range of wavelengths in which the optimum wavelength is included, the timing of changeover of the main-signal light is detected as being the moment at which the intensity ratio of two wavelengths bracketing the optimum wavelength has attained a set value, and the main signal is changed upon in response to such detection. If two wave of monitoring light are thus used, it is unnecessary to constantly monitor an increase or decrease in the intensity of the specific component in each monitoring light beam; it will suffice to compare the absolute values of the intensities of specific components of three waves at a certain time.

(e) Overview of fourth aspect (enabling any type of optical modulation scheme to be supported)

[0048]

(1) An optimum-wavelength detector detects, as optimum wavelength, the wavelength for which the intensity of a specific frequency component contained in a baseband spectrum signal of received light is minimum and outputs the light of this detected optimum wavelength to an optical transmission line during system operation.
(2) Or, in another arrangement, the optimum-wavelength detector detects, as optimum wavelength, the wavelength for which the intensity of a specific frequency component contained in a baseband spectrum signal of received light is maximum and a transmitter outputs the light of this detected optimum wavelength to the optical transmission line during system operation.
(3) Or, in another arrangement, a dispersion add-on unit is provided in front of the optimum-wavelength detector. Prior to system operation, the optimum-wavelength detector detects a wavelength λmax for which the intensity of a specific frequency component contained in a baseband spectrum signal of received light, which enters via the dispersion add-on unit, is maximum. During system operation, a transmitter outputs, to the optical transmission line, light of a wavelength so that the wavelength of the light that enters the optimum-wavelength detector via the dispersion add-on unit becomes λmax. In this case, the wavelength of light output to the optical transmission line becomes a wavelength for which the intensity of the specific frequency component contained in the baseband spectrum signal of the receiving light is minimized.
(4) Or, in another arrangement, a dispersion add-on unit is provided in front of the optimum-wavelength detector. Prior to system operation, the optimum-wavelength detector detects a wavelength λmin for which the intensity of a specific frequency component contained in a baseband spectrum signal of received light, which enters via the dispersion add-on unit, is minimum. During system operation, a transmitter outputs, to the optical transmission line, light of a wavelength so that the wavelength of the light that enters the optimum-wavelength detector via the dispersion add-on unit becomes λmin. In this case, the wavelength of light output to the optical transmission line becomes a wavelength for which the intensity of the specific frequency component contained in the baseband spectrum signal of the receiving light is maximized.

[0049] The characteristic of the intensity of the specific frequency component differs depending upon whether the optical modulation scheme is NRZ modulation, OTDM modulation or RZ modulation. Detection of optimum wavelength is possible with NRZ modulation by detecting the minimum portion at the foot of the peak of the characteristic of the intensity of the specific frequency component, with OTDM modulation by detecting the valley between two peaks and with RZ modulation by detecting a maximum value. Accordingly, by applying any of (1) to (4) above depending upon the optical modulation scheme, light of the zero-dispersion wavelength or light of a wavelength closest to this wavelength can be output to an optical transmission line.

(f) Overview of fifth aspect (wavelength multiplexing)

[0050] A wavelength-dispersion compensating function is provided to a wavelength multiplexing optical transmission system having a plurality of data transmitters, a multiplexer for combining light of different wavelengths output by these transmitters and sending the resulting light to an optical transmission line, a demultiplexer for separating light, which has been received from the optical transmission line, according to wavelength, and a plurality of receivers for identifying the data from the received light of each of the wavelengths output by the demultiplexer. More specifically, each transmitter combines and transmits main-signal light and monitoring light, each receiver detects the timing of main-signal light changeover in dependence upon fluctuation of the respective zero-dispersion wavelength, and each transmitter adopts, as main-signal light and at this timing, light generated by a light source neighboring the light source which generates the main-signal light.

(B) Principles of the present invention

(a) Use of multiple light sources

[0051] The present invention provides an optical transmission system and an optical transmitter in which use is made of multiple light sources for generating light of different wavelengths, and light of a wavelength from a prescribed light source having the optimum transmission characteristic in regard to wavelength dispersion exhibited by an optical transmission line is output to this optical transmission line, thereby compensating for dispersion.

(b) Use of a semiconductor array laser or discrete semiconductor lasers

[0052] The light source is a semiconductor array laser (Sasaki et al., "Multi-wavelength MQW-DBR laser array using MOVPE-selected growth", 1994, Electronic Information Communication Society, Autumn Meeting SC-2-2), which includes integrated lasers having a plurality of oscillation wavelengths, or a plurality of juxtaposed discrete semiconductor lasers of different wavelengths used in already existing optical communications systems.

(c) Dispersion compensation when optimum wavelength is known

[0053] If the system is one in which the optimum wavelength (e.g., zero-dispersion wavelength) is already known and a change in wavelength is small in comparison with the dispersion tolerance, light having a wavelength nearest to this optimum wavelength is output to the optical transmission line.

(d) Dispersion compensation when optimum wavelength is unknown and change in wavelength is small

[0054] If the system is one in which the optimum wavelength is unknown and a change in wavelength is small in comparison with the dispersion tolerance, then, before the optical transmission system starts operating, the light beams of different wavelengths generated by the plurality of light sources are successively output to the optical transmission line and the optimum wavelength is detected. When the system is in operation, light generated by the light source having a wavelength nearest to this detected optimum wavelength is output to the optical transmission line.

(e) Dispersion compensation when optimum wavelength is unknown and change in wavelength is large

[0055] If the system is one in which the optimum wavelength is unknown and a change in wavelength is large in comparison with the dispersion tolerance, then, before the optical transmission system starts operating, the light beams of different wavelengths generated by the plurality of light sources are successively output to the optical transmission line and the optimum wavelength is detected. When the system is in operation, light generated by the light source having a wavelength nearest to this detected optimum wavelength is output to the optical transmission line.

[0056] During operation of the system, the wavelength of the light output to the optical transmission line is changed minutely so that a new optimum wavelength (zero-dispersion wavelength) that is the result of aging can be detected. The optical transmitter changes over the light source in such a manner that the light of the optimum wavelength detected during system operation is output to the optical transmission line.

(f) Different dispersion compensation when optimum wavelength is unknown and change in wavelength is large

[0057] If the system is one in which the optimum wavelength is unknown and a change in wavelength is large in comparison with the dispersion tolerance, then, before the optical transmission system starts operating, the light beams of different wavelengths generated by the plurality of light sources are successively output to the optical transmission line and the optimum wavelength is detected. When the system is in operation, light generated by the light source having a wavelength nearest to this detected optimum wavelength is output to the optical transmission line as main-signal light.

[0058] Further, during operation of the system, monitoring light is combined with the main-signal light output to the optical transmission line, and the resulting light is output to the optical transmission line so that direction and amount of fluctuation of the optimum wavelength (zero-dispersion wavelength) due to aging can be detected. The optical transmitter changes over the light source from the current light source to a neighboring light source if the zero-dispersion wavelength fluctuates owing to aging or the like and becomes equal to a wavelength intermediate the present light source and the neighboring light source.

(g) Light-source switching method

[0059] Fig. 4 illustrates a group delay characteristic when the reference is a zero-dispersion wavelength λ_0 of 1552 nm over a transmission distance of 50 km. If we let the second-order dispersion of an optical fiber be represented by

$$dD/d\lambda = 0.07 \text{ (ps/nm2/km)} \quad (1)$$

then dispersion D will be

$$D = 0.07(\lambda-\lambda_0) \text{ (ps/nm/km)} \quad (2)$$

If Equation (2) is integrated, then delay T_D becomes as follows:

$$T_D = 0.07/2 \times (\lambda-\lambda_0)^2 + \alpha \qquad (3)$$
$$= 0.035(\lambda-\lambda_0)^2 \text{ (ps/km)}$$

The group delay characteristic is obtained from Equation (3). It should be noted that $\alpha = 0$ is assumed to hold.

[0060] From Equation (3), the group delay characteristic indicates a curve of second degree centered on the zero-dispersion wavelength λ_0. If $\lambda_0 = \lambda_1$ holds, the characteristic becomes a quadratic curve BC1. If $\lambda_0 = \lambda_2$ holds, the characteristic becomes a curve BC2 of second degree. A curve of second degree is symmetrical. Therefore, if the wavelength of the output light is switched from λ_1 to λ_2 when λ_0 becomes precisely the center wavelength $[\lambda_0 = (\lambda_1+\lambda_2)/2]$ between λ_1 and λ_2 in a case where the zero-dispersion wavelength λ_0 is changing from λ_1 (= 1552 nm) to λ_2 (= 1553.6 nm), then the signal delays before and after the wavelength changeover become equal and small, and a discontinuous change in the group delay does not occur before and after the wavelength changeover. It should be noted that λ_1, λ_2 represent the wavelengths of light generated by two neighboring light sources. In general, if λ_{n-1}, λ_n represent the wavelengths of neighboring light sources, then the zero-dispersion wavelength λ_0 when the light sources are changed over is represented by the following:

$$\lambda_0 = \lambda_{n-1} + \Delta\lambda/2 \ (\lambda_0 > \lambda_{n-1})$$
$$= \lambda_n - \Delta\lambda/2 \ (\lambda_0 < \lambda_n)$$

$$\Delta\lambda = |\lambda_{n-1}-\lambda_n|$$

[0061] If the above-cited equation is not used and wavelength of the output light is changed over from λ_1 to λ_2 when the zero-dispersion wavelength λ_0 has changed from λ_1 to the wavelength λ_2, which is 1.6 nm distant from λ_1, signal delay before and after the wavelength changeover becomes 4.5 ps, as shown in Fig. 4. This is a value that is not negligible when the transmission speed is 40 Gbps (1 bit = 25 ps), and there is the danger that this delay will cause signal degradation.

(h) Prevention of signal interruption at light-source changeover

[0062] In a case where the wavelength of the optical signal output to the optical transmission line is changed over from λ_1 to λ_2, signal interruption will occur if the light sources are merely changed over by a switch or the like. According to the present invention, signal interruption is prevented by specially contriving a method of changing over the light sources. Figs. 5A and 5B are diagrams useful in describing a method of changing over light sources without causing signal interruption. Fig. 5A shows a first light-source changeover method in which light sources are changed over while holding constant the total light-intensity signal output to the optical transmission line without controlling an optical amplifier. Fig. 5B shows a second light-source changeover method in which light sources are changed over while holding constant the total light-intensity signal output to the optical transmission line using an optical amplifier.

[0063] Fig. 6 is a diagram useful in describing control of current injected into each light-source driver in the first light-source changeover method mentioned above. With a light source D1 of wavelength λ_1 emitting light (T_0), current injected into a light source D2 of wavelength λ_2 is gradually increased to cause this light source to emit light (T_1). At this time the light intensity of light source D1 of wavelength λ_1 is weakened in such a manner that the sum of the light intensities of both light sources D1, D2 of wavelengths λ_1, λ_2 will be constant at all times. Thenceforth the light intensity of light source D2 of wavelength λ_2 is gradually increased and the light intensity of light source D1 of wavelength λ_1 gradually decreased, whereby wavelength changeover from λ_1 to λ_2 can be performed without signal interruption (T2).

[0064] The second light-source changeover method is such that when an optical amplifier is used, a sudden change in input light intensity to the optical amplifier can be avoided. In addition, it is possible to prevent the occurrence of a light surge caused by the optical amplifier. More specifically, as shown in Fig. 5B, the light source of wavelength λ_2 is cause to emit light at the same time that the light source of wavelength λ_1 is emitting light, then the light source of wavelength λ_1 is extinguished. In the case of this light-source changeover, the ratio of the intensities of λ_1, $\lambda_1+\lambda_2$, λ_2 is 1:2:1. Accordingly, the gain of the optical amplifier is regulated to perform feedback control in such a manner that the output light intensity is rendered constant.

(i) Maximum wavelength spacing of light sources

[0065] Fig. 7 illustrates the relationship between maximum wavelength spacing ($\Delta\lambda = \lambda_{n-1} - \lambda_n$) of neighboring light sources and dispersion compensation precision (= dispersion value D) when the zero-dispersion wavelength is 1552 nm. The higher the transmission speed, the finer the dispersion compensation precision necessary for the system, i.e., the finer the amount of change in the dispersion value when light sources are changed over between neighboring wavelengths, is required to be. If the zero-dispersion wavelength λ_0 is 1552 nm and the second-order dispersion of the optical fiber is 0.07 (ps/nm^2/km) for a transmission distance of 50 km, the maximum wavelength spacing $\Delta\lambda$ (nm) of the light sources with respect to allowable fluctuation D of dispersion (ps/nm) is as follows based upon Equation (2):

$$\Delta\lambda \text{ (nm)} = D \text{ (ps/nm)}/0.07 \text{ (ps/nm}^2\text{/km)} \cdot 50 \text{ (km)} \tag{4}$$

so that the wavelength spacing of the light sources can be determined from Equation (4).

(C) Embodiments

(a) Construction of transmitter having plurality of light sources

(a-1) First embodiment of optical transmitter

[0066] Fig. 8 is a diagram illustrating the construction of a first embodiment of an optical transmitter having semiconductor lasers as the plurality of light sources. Shown in Fig. 8 are the optical transmitter 10, the optical receiver 20 and the optical transmission line 30. The optical transmitter 10 includes a plurality of light sources $11a_1$ - $11a_n$ having different wavelengths (λ_1 - λ_n) and formed by a plurality of discrete semiconductor lasers; drivers $11b_1$ - $11b_n$ for driving respective ones of the semiconductor lasers; and an arrayed waveguide grating (AWG) 12a for outputting light generated by each light source. The arrayed waveguide grating 12a, which functions as a multiplexer/demultiplexer, multiplexes light of different wavelengths entering from a plurality of waveguides and outputs the light as wavelength-multiplexed light. Conversely, if wavelength-multiplexed light enters in the opposite direction, the arrayed waveguide grating 12a separates the light wavelength by wavelength and outputs the separated light to a respective one of the waveguides. Accordingly, if the arrayed waveguide grating 12a is used as a multiplexer and only a prescribed light source emits light, then the light from the light source can be output.

[0067] The optical transmitter 10 further includes an external modulator 12b in which the light output from the arrayed waveguide grating 12a is on/off-modulated by a 40-Gbps signal. By way of example, the external modulator 12b is an $LiNbO_3$ Mach-Zehnder modulator or an EA (electro-absorption) modulator. The optical transmitter 10 further includes an output wavelength controller 13 for causing prescribed ones of the drivers $11b_1$ - $11b_n$ to drive the corresponding semiconductor lasers into light emission, thereby changing the wavelength of the light output to the optical transmission line.

[0068] Accordingly, if the output wavelength controller 13 acquires the zero-dispersion wavelength of the optical transmission line 30, the controller 13 drives the light source that will generate light having a wavelength nearest to this zero-dispersion wavelength so that this light is output to the optical transmission line to compensate for dispersion.

(a-2) Second embodiment of optical transmitter

[0069] Fig. 9 is a diagram illustrating the construction of a second embodiment of an optical transmitter having semiconductor lasers as the plurality of light sources. Components identical with those of the first embodiment shown in Fig. 8 are designated by like reference characters. This embodiment differs from the first embodiment in that a star coupler 12c is used instead of the arrayed waveguide grating 12a for multiplexing light; the two embodiments are exactly the same in other aspects of construction and in terms of operation.

(a-3) Third embodiment of optical transmitter

[0070] Figs. 10A and 10B are diagrams showing a third embodiment of an optical transmitter having semiconductor lasers as the plurality of light sources. Components identical with those shown in Figs. 8 and 9 are designated by like reference characters.

[0071] The optical transmitter of Fig. 10A differs from that of Fig. 8 in that lasers (MI-DFB-LD) $11c_1$ - $11c_n$ with built-in modulators are used as the semiconductor lasers and the external modulator 12b is omitted. The semiconductor lasers with built-in modulators are obtained by forming semiconductor lasers $11a_1$ - $11a_n$ and modulator portions $11c_1'$ - $11c_n'$ on the same substrate.

[0072] The optical transmitter of Fig. 10B differs from that of Fig. 9 in that lasers (MI-DFB-LD) $11c_1$ - $11c_n$ with built-in modulators are used as the semiconductor lasers and the external modulator 12b is omitted.

(a-4) Fourth embodiment of optical transmitter

[0073] Fig. 11 is a diagram illustrating the construction of a fourth embodiment of an optical transmitter having a semiconductor array laser as the plurality of light sources. Components identical with those of the first embodiment shown in Fig. 8 are designated by like reference characters. This embodiment differs from the first embodiment in that a semiconductor array laser 11d is used instead of the semiconductor lasers as the plurality of light sources. In accordance with the fourth embodiment, lasers having the required wavelength spacing can be realized on one wafer, thereby lowering cost and reducing size.

(a-5) Fifth embodiment of optical transmitter

[0074] Fig. 12 is a diagram illustrating the construction of a fifth embodiment of an optical transmitter having a semiconductor array laser as the plurality of light sources. Components identical with those of the second embodiment shown in Fig. 9 are designated by like reference characters. This embodiment differs from the second embodiment in that the semiconductor array laser 11d is used instead of the semiconductor lasers as the plurality of light sources.

(b) Dispersion compensation when optimum wavelength is known

[0075] If the system is one in which the optimum wavelength (e.g., zero-dispersion wavelength) is already known and a change in wavelength is small in comparison with the dispersion tolerance, light having the optimum wavelength is output to the optical transmission line, thereby making it possible to compensate for waveform degradation caused by dispersion exhibited by the optical transmission line.

[0076] Fig. 13 is a diagram showing the construction of a first embodiment of an optical transmission system which performs dispersion compensation when optimum wavelength is known. Shown in Fig. 13 are the optical transmitter 10, the optical receiver 20 and the optical transmission line 30. The optical transmitter 10 includes a plurality of light sources 11_1 - 11_n having different wavelengths (λ_1 - λ_n) and constituted by a plurality of discrete semiconductor lasers or a semiconductor array laser; a multiplexer 12, which can comprise an arrayed waveguide grating, a star coupler or the like; and the external modulator 12b in which the light output from the arrayed waveguide grating 12 is on/off-modulated by a 40-Gbps signal. By way of example, the external modulator 12b is an $LiNbO_3$ Mach-Zehnder modulator or an EA (electro-absorption) modulator. The optical transmitter 10 further includes the output wavelength controller 13 for causing prescribed ones of the light sources to emit light, thereby changing the wavelength of the light output to the optical transmission line.

[0077] If the optimum wavelength, e.g., the zero-dispersion wavelength, is set, the output wavelength controller 13 causes light to be emitted only from the light source that generates light having a wavelength nearest to the zero-dispersion wavelength. The multiplexer 12 inputs the light output by this light source to the external modulator 12b, which on/off-modulates the input light by the 40-Gbps signal and outputs the modulated light to the optical transmission line 30.

[0078] Fig. 14 shows a modification of the first embodiment, in which components identical with those of the first embodiment are designated by like reference characters. Whereas the first embodiment shown in Fig. 13 is for a case where transmission is performed without a repeater, the present invention is applicable also to a case where multiple repeaters are used in transmission, as illustrated in Fig. 14. This modification includes optical transmission lines 30a - 30n and repeaters 31a, 31b, • • •. Though transmission without repeaters is illustrated in the embodiments that follow, the present invention is applicable also to a case where multiple repeaters are used in transmission.

(c) Dispersion compensation when optimum wavelength is unknown and change in wavelength is small

[0079] If the system is one in which the optimum wavelength is unknown and a change in wavelength is small in comparison with the dispersion tolerance, then, (1) before the optical transmission system starts operating, light beams of different wavelengths generated by the plurality of light sources are successively output to the optical transmission line and the optimum wavelength is detected, and (2) when the system is in operation, light generated by the light source having a wavelength nearest to this detected optimum wavelength is output to the optical transmission line.

[0080] Fig. 15 is a diagram showing the construction of an optical transmission system which performs dispersion compensation when optimum wavelength is unknown and change in wavelength is small in comparison with dispersion tolerance. Shown in Fig. 15 are the optical transmitter 10, the optical receiver 20, the outgoing optical transmission line 30, the dispersion monitor (optimum-wavelength detector) 40 for detecting a wavelength (e.g., the zero-dispersion wavelength) whose transmission characteristic is optimum in regard to wavelength dispersion of the optical transmission line, the incoming optical transmission line 50, a dispersion monitoring signal transmitter 51 for transmitting the result of dispersion monitoring, and a dispersion monitoring signal receiver 52 for extracting the result of monitoring and inputting the result to the optical transmitter 10.

[0081] The optical transmitter 10 includes the plurality of light sources 11_1 - 11_n having different wavelengths (λ_1 - λ_n) and constituted by a plurality of discrete semiconductor lasers or a semiconductor array laser; the multiplexer 12, which can comprise an arrayed waveguide grating, a star coupler or the like; the external modulator 12b in which the light output from the arrayed waveguide grating 12 is on/off-modulated by a 40-Gbps signal; the output wavelength controller 13 for causing prescribed ones of the light sources 11_1 - 11_n to emit light, thereby changing the wavelength of the light output to the optical transmission line, and outputting light of the optimum wavelength to the optical transmission line based upon the result of detection by the dispersion monitor 40.

[0082] If the wavelength of the light output to the optical transmission line 30 is equal to the zero-dispersion wavelength of the optical transmission line, the dispersion monitor 40 detects the optimum wavelength by utilizing the fact that the intensity of a specific frequency component of the received baseband spectrum signal is minimum. For example, if a 40-Gbps signal is transmitted, the specific frequency is 40 GHz (see Figs. 76A - 77B). The dispersion monitor 40 includes a light receiver 40a such as a photodiode for converting light, which has been branched from the optical transmission line 30, to an electric signal; a band-pass filter (BPF) 40b having the specific frequency as its center frequency; and an intensity detector 40c for detecting the timing at which a specific frequency component, e.g., the 40-GHz component, attains the minimum value.

[0083] If the system is one in which the optimum wavelength is known and a change in wavelength is small in comparison with the dispersion tolerance, then, before the optical transmission system starts operating, the output wavelength controller 13 causes the light sources 11_1 - 11_n to emit light successively at prescribed intervals. As a result, the light multiplexer 12 successively inputs light of wavelengths λ_1 - λ_n generated by the plurality of light sources to the external modulator 12b, which on/off modulates the input light of the different wavelengths λ_1 - λ_n by the 40-Gbps signal and outputs the modulated light to the optical transmission line 30.

[0084] The dispersion monitor 40 detects the timing at which the 40-GHz component intensity of the received baseband spectrum signal attained the minimum value and inputs the timing to the dispersion monitoring signal transmitter 51. The latter sends the timing data to the transmitting side via the optical transmission line 50, and the dispersion monitoring signal receiver 52 extracts the monitoring result (the timing data) and inputs this to the output wavelength controller 13. The latter identifies the zero-dispersion wavelength from the wavelength of the light output to the optical transmission line 30 at the timing at which the intensity of the specific frequency component attained the minimum value.

[0085] During system operation, the output wavelength controller 13 causes light to be emitted only from the light source that generates light having this zero-dispersion wavelength, so that the light having the zero-dispersion wavelength is output to the optical transmission line 30. As a result, light of a wavelength whose transmission characteristic is optimum in regard to wavelength dispersion of the optical transmission line 30 is output, thereby making it possible to compensate for dispersion.

[0086] Fig. 16 is a diagram showing the construction of a transceiver 55 equipped with the dispersion monitoring signal transmitter 51 (Fig. 15). Shown in Fig. 16 are a demultiplexer 55a, an electrical interface (signal processor) 55b, a multiplexer 55c and a transmitter 55d. The electrical interface 55b accepts the monitoring result (timing data) that enters from a processor 40d of the dispersion monitor 40, inserts the data into the data section or overhead section of a transmission signal, sends the signal to the outgoing optical transmission line 50 via the multiplexer 55c and transmitter 55d. Thus, the dispersion monitoring signal transmitter 51 of Fig. 15 is implemented by the functions possessed by the electrical interface 55b, multiplexer 55c and transmitter 55d.

[0087] Fig. 17 is a modification of the embodiment illustrated in Fig. 15. This is an example in which the dispersion compensation method of Fig. 15 is applied to an optical transmission system, which has been subjected to approximately 100% dispersion compensation using a fixed-dispersion compensator 56, in a case where the optical transmission line 30 is a high-dispersion single-mode fiber (SMF). Even this 100 dispersion-compensated optical transmission system can be subjected to dispersion compensation by sweeping wavelength via light-source switching and detecting the zero-dispersion wavelength.

[0088] In the case of transmission using multiple repeaters, the fixed-dispersion compensator would be placed on the sending side, receiving side and repeater side.

[0089] Fig. 18 illustrates the construction of another embodiment of an optical transmission system for performing dispersion compensation in a case where optimum wavelength is unknown and change in wavelength is small in comparison with dispersion tolerance. Components identical with those of the embodiment shown in Fig. 15 are designated by like reference characters. This embodiment differs from the embodiment of Fig. 15 in that:

(1) attenuators (ATT) 14_1 - 14_n for attenuating light are provided at the outputs of the light sources 11_1 - 11_n and have their outputs applied to the multiplexer 12;
(2) the light sources 11_1 - 11_n emit light at all times; and
(3) the light attenuators 14_1 - 14_n are turned on and off under the control of the output wavelength controller 13 so

that only light from a prescribed light source is input to the optical output unit 12.

[0090] Before the system is placed in operation, all of the light sources 11_1 - 11_n are made to emit light and all of the light attenuators 14_1 - 14_n are turned on to attenuate the light from respective ones of the light sources. Under these conditions the output wavelength controller 13 performs control in such a manner that the light attenuators 14_1 - 14_n corresponding to the light sources 11_1 - 11_n are turned off successively one at a time (i.e., only one is turned off and the others are turned on) at prescribed time intervals so that light from the light sources 11_1 - 11_n enters the multiplexer 12 in successive fashion. As a result, the multiplexer 12 successively inputs, to the external modulator 12b, light of different wavelengths λ_1 - λ_n generated by the light sources, and the external modulator 12b on/off-modulates the input light by the 40-Gbps signal and outputs the modulated light of different wavelengths λ_1 - λ_n to the optical transmission line 30.

[0091] The dispersion monitor 40 detects the timing at which the intensity of the 40-GHz component in the received baseband spectrum signal attains the minimum value, the dispersion monitoring signal transmitter 51 sends this timing data to the side of the transmitter, and the dispersion monitoring signal receiver 52 extracts the monitoring result (timing data) and inputs this data to the output wavelength controller 13. The output wavelength controller 13 identifies the zero-dispersion wavelength from the wavelength of the light output to the optical transmission line 30 at the timing at which the intensity of the specific frequency component attained the minimum value.

[0092] During system operation, the output wavelength controller 13 turns off only the light attenuator corresponding to the light source that generates light having this zero-dispersion wavelength, so that the light having the zero-dispersion wavelength is output to the optical transmission line 30. As a result, light of a wavelength whose transmission characteristic is optimum in regard to wavelength dispersion of the optical transmission line 30 is output, thereby making it possible to compensate for dispersion.

[0093] Fig. 19 illustrates the construction of another embodiment of an optical transmission system for performing dispersion compensation in a case where optimum wavelength is unknown and change in wavelength is small in comparison with dispersion tolerance. Components identical with those of the embodiment shown in Fig. 15 are designated by like reference characters. This embodiment differs from the embodiment of Fig. 15 in that:

(1) A variable-wavelength filter 15 is provided between the multiplexer 12 and external modulator 12b and passes, i.e., outputs, only light having a designated wavelength;
(2) the light sources 11_1 - 11_n emit light at all times;
(3) The multiplexer 12 multiplexes light of different wavelengths λ_1 - λ_n generated by the light sources 11_1 - 11_n, respectively, and inputs the light to the variable-wavelength filter 15; and
(4) the wavelength of the light output by the variable-wavelength filter 15 is controlled by the output wavelength controller 13.

[0094] Fig. 20 is a diagram showing the construction of the variable-wavelength filter. As shown in Fig. 20, the filter includes a SAW waveguide 15a formed on a substrate which exhibits an electro-optic effect, such as a substrate made of $LiNbO_3$ (lithium niobate); an interdigital transducer (IDT) 15b; a SAW clad 15c formed by diffusing titanium so as to clad the SAW waveguide; absorbers 15d, 15e for absorbing surface acoustic waves (SAW); optical waveguides 15f, 15g formed by diffusing titanium; crossed polarization beam splitters (PBS) 15h, 15i, which are arranged to embrace two linear waveguides, for operating independently of polarization; and a high-frequency signal application unit 15j for applying a high-frequency signal of 170 - 180 MHz to the interdigital transducer 15b. The high-frequency signal application unit 15j includes a high-frequency generator 15j-1 and an inductance 15j-2, which is for canceling the input capacitance of the interdigital transducer 15b, connected in series with the high-frequency generator 15j-1. When the high-frequency signal is applied to the interdigital transducer 15b, a surface acoustic wave is generated, which has the effect of rotating, by 90°, the polarization of a specific wavelength in conformity with this frequency. Accordingly, the polarization beam splitters 15h, 15i are provided on the input and output sides, respectively, to split the polarization, thereby making it possible to realize a variable-wavelength filter. For example, if wavelength-multiplexed light of the TE mode is input to the variable-wavelength filter 15 as input light, only the polarization of the wavelength corresponding to the frequency of the high-frequency signal applied to the interdigital transducer is rotated 90°, whereby TM-mode polarization is obtained. The TM-mode polarized light is output from the optical waveguide 15g.

[0095] Fig. 21 shows the tuning characteristic of the variable-wavelength filter. The frequency of the high-frequency signal is plotted along the horizontal axis and the selected wavelength along the vertical axis. The selected wavelength shortens in inverse proportion to the frequency of the high-frequency signal.

[0096] Accordingly, the variable-wavelength filter 15 is capable of selectively outputting, in successive fashion, the wavelengths contained in the input light by sweeping, at prescribed cycles, the frequency of the high-frequency signal output from the high-frequency signal application unit 15j under the control of the output wavelength controller 13.

[0097] Prior to the start of system operation, all of the light sources 11_1 - 11_n emit light, the light of the different wavelengths λ_1 - λ_n generated by the respective light sources 11_1 - 11_n is multiplexed by the multiplexer 12 and the multiplexed light is input to the variable-wavelength filter 15. Under these conditions, the output wavelength controller 13 controls the variable-wavelength filter 15 so that the light of the wavelengths λ_1 - λ_n is input to the external modulator 12b in order at predetermined time intervals. The external modulator 12b on/off-modulates the input light of different wavelengths λ_1 - λ_n by the 40-Gbps signal and outputs the modulated light to the optical transmission line 30.

[0098] The dispersion monitor 40 detects the timing at which the intensity of the 40-GHz component in the received baseband spectrum signal attains the minimum value, the dispersion monitoring signal transmitter 51 sends this timing data to the side of the transmitter, and the dispersion monitoring signal receiver 52 extracts the monitoring result (timing data) and inputs this data to the output wavelength controller 13. The output wavelength controller 13 identifies the zero-dispersion wavelength from the wavelength of the light output to the optical transmission line 30 at the timing at which the intensity of the specific frequency component attained the minimum value.

[0099] During system operation, the output wavelength controller 13 controls the variable-wavelength filter 15 so as to output the light of the zero-dispersion wavelength to the optical transmission line 30. As a result, light of a wavelength whose transmission characteristic is optimum in regard to wavelength dispersion of the optical transmission line 30 is output, thereby making it possible to compensate for dispersion.

(d) Dispersion compensation when optimum wavelength is unknown and change in wavelength is large

[0100] If the system is one in which the optimum wavelength is unknown and a change in wavelength is large in comparison with the dispersion tolerance, then, (1) before the optical transmission system starts operating, light beams of different wavelengths generated by the plurality of light sources are successively output to the optical transmission line and the optimum wavelength is detected, and (2) when the system is in operation, light generated by the light source having a wavelength nearest to this detected optimum wavelength is output to the optical transmission line. (3) Further, during system operation, the wavelength of the light output to the optical transmission line is changed minutely so that the zero-dispersion wavelength can be detected even if it changes owing to aging, and (4) when the zero-dispersion wavelength has changed to a wavelength intermediate the present light source and a neighboring light source owing to aging, the optical transmitter changes over the light source from the present light source to the neighboring light source to thereby change the wavelength of the light output to the optical transmission line. By changing over wavelength at the wavelength intermediate the present light source and the neighboring light source, signal delays before and after the wavelength changeover can be made equal and small, and a discontinuous change in the group delay does not occur before and after the wavelength changeover. This makes it possible to eliminate signal degradation.

[0101] Fig. 22 illustrates the construction of an optical transmission system for performing dispersion compensation in a case where optimum wavelength is unknown and change in wavelength is large in comparison with dispersion tolerance. Components identical with those of the embodiment shown in Fig. 15 are designated by like reference characters. This embodiment differs from the embodiment of Fig. 15 in that:

(1) the wavelength of light output to the optical transmission line is varied during system operation;
(2) the light sources (e.g., semiconductor lasers) 11_1 - 11_n are provided with ATC circuits (automatic temperature-control circuits) 16_1 - 16_n, respectively, for regulating light-source temperature to a set temperature; and
(3) a temperature-varying controller 17 for varying the temperature of the light source which generates the light being output to the optical transmission line, thereby varying the wavelength of the output light.

[0102] According to the embodiment of Fig. 22, when the zero-dispersion wavelength of the optical transmission line 30 varies by $\Delta\lambda/2$ (where $\Delta\lambda$ is the light-source wavelength spacing), the light source is switched from the present light source to a neighboring light source. In order to so arrange it that a $\Delta\lambda/2$-change in zero-dispersion wavelength can be detected, it is required that the wavelength of light output to the optical transmission line 30 be varied by $\pm\Delta\lambda/2$ or greater. Since the light sources 11_1 - 11_n are such that the wavelength of output light varies depending upon ambient temperature, the temperature of the semiconductor lasers is controlled in such a manner that the wavelength of output light will vary over a range of $-\lambda'$ to $+\lambda'$ (where $\lambda' > \Delta\lambda/2$ holds).

[0103] Fig. 23 illustrates an example of an ATC circuit, in which numeral 11 denotes a semiconductor laser (LD) serving as a light source. Shown in Fig. 23 are a Peltier element 16a for heating and cooling the LD chip depending upon the direction of current; a thermister 16b having a negative resistance characteristic for detecting the temperature of the LD chip; a package 16c for accommodating the semiconductor laser, the Peltier element and the thermister; resistors 16d, 16e; PNP and NPN transistors 16f, 16g, respectively; and a comparator 16h having an inverting terminal to which a voltage (a voltage conforming to the temperature of the LD) Vt obtained by potential division using the thermister 16b and resistor 16d is applied, a non-inverting terminal to which a reference voltage Vref is applied, and an output terminal connected to the bases of the transistors 16f, 16g. The emitter of the PNP transistor 16f is connected to

V+, the emitter of the NPN transistor 16g is connected to V-, and the collectors of both transistors are connected to the Peltier element 16a.

[0104] When the temperature of the light source 11 is low, the resistance of the thermister 16b increases, the voltage Vt decreases such that Vt < Vref holds and the output of the comparator 16h becomes positive. As a result, the transistor 16f turns off, the transistor 16g turns on and current flows through the Peltier element in a direction that produces heat, thereby heating the interior of the package and raising the temperature of the LD. When the LD temperature rises, the resistance of the thermister declines, the voltage Vt increases such that Vt > Vref holds and the output of the comparator 16h becomes negative. As a result, the transistor 16f turns on, the transistor 16g turns off and current flows through the Peltier element in a direction that produces cooling, thereby lowering the temperature of the LD. Accordingly, control can be performed in such a manner that the LD temperature becomes a set temperature.

[0105] If the optimum wavelength is unknown and the change in wavelength is large in comparison with the dispersion tolerance, then, prior to the start of system operation, first the output wavelength controller 13 causes the light sources 11_1 - 11_n to emit light successively at predetermined time intervals. As a result, the multiplexer 12 successively inputs, to the external modulator 12b, light of different wavelengths λ_1 - λ_n generated by the plurality of light sources, and the external modulator 12b on/off-modulates the input light of different wavelengths λ_1 - λ_n by the 40-Gbps signal and outputs the modulated light to the optical transmission line 30.

[0106] The dispersion monitor 40 detects the timing at which the intensity of the 40-GHz component in the received baseband spectrum signal attains the minimum value and inputs the timing to the dispersion monitoring signal transmitter 51. The relationship between wavelength and monitoring component intensity can be approximated by a curve of second degree, as illustrated in Fig. 24. Then the wavelength of output light is equal to the zero-dispersion wavelength, intensity takes on the minimum value. Accordingly, the timing at which the intensity of the monitoring component attains the minimum value is detected and input to the dispersion monitoring signal transmitter 51.

[0107] The dispersion monitoring signal transmitter 51 sends this timing data to the side of the transmitter and the dispersion monitoring signal receiver 52 extracts the monitoring result (timing data) and inputs this data to the output wavelength controller 13. The output wavelength controller 13 identifies λ_1 as being the zero-dispersion wavelength from the wavelength λ_1 of the light output to the optical transmission line 30 at the timing at which the intensity of the specific frequency component attained the minimum value (see the broken line in Fig. 24).

[0108] During system operation, the output wavelength controller 13 causes only the light source (referred to as the "present light source") that generates light having the zero-dispersion wavelength λ_1 to emit light, so that this light is output to the optical transmission line 30. As a result, light of a wavelength whose transmission characteristic is optimum in regard to wavelength dispersion of the optical transmission line 30 is output, thereby making it possible to compensate for dispersion.

[0109] Further, during system operation, the temperature-varying controller 17 controls the ATC circuit of the present light source so as to vary the temperature of this light source. That is, the temperature-varying controller 17 varies the wavelength of the output light by successively changing the set temperature at a period of time T necessary to regulate temperature to a constant value.

[0110] The dispersion monitor 40 detects the timing at which the intensity of the 40-GHz component in the received baseband spectrum signal attains the minimum value and sends this timing to the output wavelength controller 13. The latter refers to a table (not shown), which is for converting set temperature to wavelength, based upon the set temperature prevailing at the received timing, thereby obtaining the wavelength λ' of the light being output to the optical transmission line 30 and identifying the zero-dispersion wavelength from this wavelength. Next, the output wavelength controller 13 checks to determine whether the zero-dispersion wavelength has changed by one-half [$= \Delta\lambda/2 = (\lambda_2-\lambda_1)/2$] of the light-source wavelength spacing $\Delta\lambda$ ($= \lambda_2-\lambda_1$), which can be caused by aging of the optical transmission line. If the change is less than $\Delta\lambda/2$, the light source is not changed over. However, if the change is equal to or greater than $\Delta\lambda/2$, then the light source is changed over from the present light source to the neighboring light source, as indicated by the solid line in Fig. 24.

[0111] In the foregoing a case is described in which the present invention is applied to an optical transmitter in which only one light source emits light. However, as shown in Fig. 25, the present invention can be applied also to a transmitter in which the light attenuators 14_1 - 14_n are provided between the respective light sources 11_1 - 11_n and the multiplexer 12, all of the light sources are made to emit light constantly and only a prescribed light attenuator is turned off, whereby light from the light source corresponding to this attenuator is output to the optical transmission line 30. Further, as shown in Fig. 26, the present invention can be applied also to a transmitter in which the variable-wavelength filter 15 is provided, all of the light sources are made to emit light constantly and light having a desired wavelength is output to the optical transmission line by the variable-wavelength filter 15.

(e) Other example of dispersion compensation when optimum wavelength is unknown and change in wavelength is large

[0112] If the system is one in which the optimum wavelength is unknown and a change in wavelength is large in comparison with the dispersion tolerance, then, (1) before the optical transmission system starts operating, light beams of different wavelengths generated by the plurality of light sources are successively output to the optical transmission line and the optimum wavelength is detected, and (2) when the system is in operation, light generated by the light source having a wavelength nearest to this detected optimum wavelength is output to the optical transmission line as main-signal light. (3) Further, during system operation, monitoring light is multiplexed with the main-signal light and is output to the optical transmission line so that direction and amount of fluctuation of the optimum wavelength (zero-dispersion wavelength) due to aging can be detected, and (4) when the zero-dispersion wavelength changes to a wavelength intermediate the present light source and the neighboring light source owing to aging, the optical transmitter changes over the light source from the present light source to the neighboring light source to thereby change the wavelength of the light output to the optical transmission line. By changing over wavelength at the wavelength intermediate the present light source and the neighboring light source, signal delays before and after the wavelength changeover can be made equal and small, and a discontinuous change in the group delay does not occur before and after the wavelength changeover. This makes it possible to eliminate signal degradation.

[0113] Figs. 27A and 27B are diagrams useful in describing the principle through which the direction of a change in zero-dispersion wavelength and the fact that the zero-dispersion wavelength has changed to a wavelength intermediate the wavelengths of the present light source and neighboring light source are detected using the main-signal light and the monitoring light. As shown in Figs. 27A, 27B, the relationship between wavelength and intensity of the monitoring component (the 40-GHz component) can be approximated by a curve of second degree. Intensity takes on the minimum value when the wavelength of output light is the zero-dispersion wavelength. When the zero-dispersion wavelength λ of the optical transmission line is λ_0 ($\lambda = \lambda_0$), the wavelength of the main-signal light output from a prescribed light source is λ_1 and the wavelength of the monitoring light output by the neighboring light source is λ_2, the relationship between wavelength and intensity of the monitoring component takes on a characteristic indicated by the broken line in Fig. 27A. Here the monitoring signal intensity at wavelength λ_1 is $P(\lambda_1)1$ and the monitoring signal intensity at wavelength λ_2 is $P(\lambda_2)1$. If the zero-dispersion wavelength fluctuates from this state toward the side of long wavelength ($\lambda = \lambda'$), the relationship between wavelength and monitoring component intensity changes to a characteristic indicated by the solid line in Fig. 27A. Consequently, the monitoring signal intensity at wavelength λ_1 becomes $P(\lambda_1)2$ and the monitoring signal intensity at wavelength λ_2 becomes $P(\lambda_2)2$. In other words, if the zero-dispersion wavelength λ fluctuates toward the side of longer wavelength, the intensity of the monitoring component of the main-signal light wavelength (λ_1) increases and the intensity of the monitoring component of the monitoring light wavelength (λ_2) decreases.

[0114] On the other hand, if the zero-dispersion wavelength fluctuates from the state indicated by the dot-and-dash line of Fig. 27B toward the side of short wavelength ($\lambda = \lambda'$), the relationship between wavelength and monitoring component intensity changes to a characteristic indicated by the solid line in Fig. 27B. Consequently, the monitoring signal intensity at wavelength λ_1 decreases and the monitoring signal intensity at wavelength λ_2 increases. In other words, if the zero-dispersion wavelength λ fluctuates toward the side of shorter wavelength, the intensity of the monitoring component of the main-signal light wavelength (λ_1) decreases and the intensity of the monitoring component of the monitoring light wavelength (λ_2) increases.

[0115] Thus, the direction in which the zero-dispersion wavelength fluctuates can be detected from the direction of increase/decrease of the intensity of the monitoring component (the 40-GHz component) at the wavelength (λ_1) of the main-signal light and at the wavelength (λ_2) of the monitoring light. Further, when the zero-dispersion wavelength has changed to a wavelength intermediate the wavelength λ_1 of the main-signal light and the wavelength λ_2 of the monitoring light (namely a wavelength intermediate the wavelength of the present light source and the wavelength of the neighboring light source), the monitoring component intensity at the wavelength λ_1 and the monitoring component intensity at the wavelength λ_2 become equal owing to the symmetry of the curve of second degree. In other words, by detecting the fact that the monitoring component intensities at the wavelengths λ_1, λ_2 have become equal, the fact that the zero-dispersion wavelength has changed to a wavelength intermediate the wavelengths of the present light source and neighboring light source can be detected. It should be noted that if the zero-dispersion wavelength λ fluctuates and becomes less than the wavelength of the main-signal light or greater than the wavelength of the main-signal light, the monitoring component intensities at the wavelength (λ_1) of the main-signal light and at the wavelength (λ_2) of the monitoring light both increase or both decrease before and after the fluctuation.

[0116] Fig. 28 illustrates the construction of an optical transmission system for performing dispersion compensation in a case where optimum wavelength is unknown and change in wavelength is large in comparison with dispersion tolerance. Shown in Fig. 28 are the optical transmitter 10, the optical receiver 20, the outgoing optical transmission line 30, a first variable-wavelength optical filter 41 for passing main-signal light, a second variable-wavelength optical filter

42 for passing monitoring light, and wavelength dispersion monitors 43, 44 having a construction identical with that of the wavelength dispersion monitor 40 in the foregoing embodiments.

[0117] The wavelength dispersion monitor 43 monitors the 40-GHz component contained in the main-signal light of wavelength λ_1 and outputs the monitoring component intensity, and the wavelength dispersion monitor 44 monitors the 40-GHz component contained in the monitoring light of wavelength λ_2 (> λ_1) and outputs the monitoring component intensity. On the basis of the monitoring component intensities that enter from the wavelength dispersion monitors 43 and 44, the dispersion compensation control unit 45 determines (1) the direction of a change in zero-dispersion wavelength, (2) the fact that the zero-dispersion wavelength has changed to a wavelength intermediate the wavelengths of the present light source and neighboring light source, and (3) that the zero-dispersion wavelength is less than the wavelength of the main-signal light or greater than the wavelength of the main-signal light, and, on the basis of the results of the determinations made, controls the wavelength setting of the optical filters 41, 42 and controls the switching of the light sources. Also shown in Fig. 28 are the incoming optical transmission line 50, the dispersion monitoring signal transmitter 51 for transmitting the signal (result of monitoring, a light-source changeover command, etc.) that enters from the dispersion compensation control unit 45, and the dispersion monitoring signal receiver 52 for extracting the result of monitoring and the light-source changeover command and inputting the same to the optical transmitter 10.

[0118] The optical transmitter 10 includes the plurality of light sources 11_1 - 11_n having different wavelengths (λ_1 - λ_n) and constituted by a plurality of discrete semiconductor lasers or a semiconductor array laser; the multiplexer 12, which can comprise an arrayed waveguide grating, a star coupler or the like; the external modulator 12b in which the light output from the arrayed waveguide grating 12 is on/off-modulated by a 40-Gbps signal; the output wavelength controller 13 for causing prescribed ones of the light sources 11_1 - 11_n to emit light, thereby changing the wavelength of the light output to the optical transmission line and, when the system is operating, outputting light of the optimum wavelength to the optical transmission line as main-signal light, multiplexing monitoring light with the main-signal light and outputting the result to the optical transmission line.

[0119] If the optimum wavelength is unknown and the change in wavelength is large in comparison with the dispersion tolerance, then, before the optical transmission system starts operating, light of all wavelengths enters the wavelength dispersion monitor 43. Under these conditions, the output wavelength controller 13 causes the light sources 11_1 - 11_n to successively emit light at predetermined time intervals. As a result, the light multiplexer 12 successively inputs light of different wavelengths λ_1 - λ_n generated by the plurality of light sources to the external modulator 12b, which modulates the input light of he different wavelengths λ_1 - λ_n by the 40-Gbps signal and outputs the modulated light to the optical transmission line 30.

[0120] The dispersion monitor 43 detects the timing at which the 40-GHz component intensity of the received baseband spectrum signal attained the minimum value and inputs the timing to the dispersion compensation control unit 45. The latter sends this timing to the transmitting side via the dispersion monitoring signal transmitter 51. The dispersion monitoring signal receiver 52 extracts the monitoring result (the timing data) and inputs this to the output wavelength controller 13. The latter identifies wavelength λ, which was being output to the optical transmission line 30 at the timing at which the monitoring component intensity attained the minimum value, as the zero-dispersion wavelength. Of the light-source wavelengths λ_1, λ_2 bracketing the zero-dispersion wavelength λ, the wavelength λ_1 nearest the zero-dispersion wavelength λ is adopted as the wavelength of the main-signal light, and λ_2 is adopted as the wavelength of the monitoring light. From this point onward, wavelength-dispersion compensation control at the time of system operation is executed in accordance with the flowchart shown in Fig. 29.

[0121] It should be noted that if the optimum wavelength is known and the change in wavelength is large in comparison with dispersion tolerance, then wavelength-dispersion compensation control at the time of system operation is executed immediately in accordance with the flowchart shown in Fig. 29 using the wavelength λ_1 nearest the zero-dispersion wavelength λ as the wavelength of the main-signal light and the wavelength λ_2 as the wavelength of the monitoring light, where the light-source wavelengths λ_1, λ_2 bracket the zero-dispersion wavelength λ.

[0122] When the system is in operation, the dispersion compensation control unit 45 sets the wavelength λ_1 of the main-signal light as the center wavelength of the first optical filter 41 and sets the wavelength λ_2 of the monitoring light as the center wavelength of the second optical filter 42 (step 101). Further, the output wavelength controller 13 causes the light source of the main-signal light to emit light so that this light is output to the optical transmission line 30. As a result, light of a wavelength whose transmission characteristic is optimum in regard to wavelength dispersion of the optical transmission line 30 is output, thereby making it possible to compensate for dispersion.

[0123] Further, during system operation, the output wavelength controller 13 causes the monitoring light source to emit light so that the monitoring light of wavelength λ_2 will be multiplexed with the main-signal light (step 102).

[0124] On the basis of the wavelength (λ_1) of the main-signal light that enters from the wavelength dispersion monitors 43, 44 and the monitoring component intensity (the 40-GHz component) at the monitoring light wavelength (λ_2), the dispersion compensation control unit 45 checks to determine whether the zero-dispersion wavelength λ has changed to a wavelength intermediate the wavelength of the present light source and the wavelength of the neighboring light source (step 103). If the zero-dispersion wavelength has not changed to the intermediate wavelength, the processing of step 102 is executed. If the zero-dispersion wavelength has changed to the intermediate wavelength, however, the dispersion compensation control unit 45 identifies the direction in which the zero-dispersion wavelength λ changed (step 104, 105). If the zero-dispersion wavelength λ changed toward the side of longer wavelength, the dispersion compensation control unit 45 performs control in such a manner that the center wavelength of the first optical filter 41 is shifted so that the wavelengths λ_1, λ_2 will fall within the range of the filter (step 106). Next, the dispersion compensation control unit 45 instructs the output wavelength controller 13 to switch the light source of the main-signal light to the neighboring light source on the side of longer wavelength. In response, the output wavelength controller 13 causes the light source of wavelength λ_2 to emit light in addition to the light source of λ_1 and subsequently extinguishes the light source of wavelength λ_1 (step 107). As a result, the wavelength of the main-signal light can be changed over to the side of longer wavelength without any interruption in light.

[0125] If the zero-dispersion wavelength changed toward the side of shorter wavelength such that $\lambda_0 < \lambda < \lambda_1$ holds, the dispersion compensation control unit 45 sets λ_0 in the second optical filter 42 as the center wavelength. Further, at this time the dispersion compensation control unit 45 instructs the output wavelength controller 13 to cause the light source of monitoring light of wavelength λ_0 to emit light instead of the light source of wavelength λ_2. Dispersion compensation control is thenceforth carried out within the range $\lambda_0 < \lambda < \lambda_1$. If the zero-dispersion wavelength fluctuates toward the side of shorter wavelength and changes to a wavelength that is intermediate λ_0 and λ_1, then the dispersion compensation control unit 45 performs control in such a manner that the center wavelength of the first optical filter 41 is shifted so that the wavelengths λ_0, λ_1 will fall within the range of the filter (step 108). Next, the dispersion compensation control unit 45 instructs the output wavelength controller 13 to switch the light source of the main-signal light to the neighboring light source on the side of shorter wavelength. In response, the output wavelength controller 13 causes the light source of wavelength λ_0 to emit light in addition to the light source of λ_1 and subsequently extinguishes the light source of wavelength λ_1 (step 109). As a result, the wavelength of the main-signal light can be changed over to side of shorter wavelength without any interruption in light.

[0126] Fig. 30 is a diagram useful in describing control for changing over wavelength when the wavelength of the main-signal light is changed over to the side of longer wavelength. In Fig. 30, W represents the wavelength filtering width of the first optical filter 41. If the zero-dispersion wavelength fluctuates toward the side of longer wavelength and changes to a wavelength intermediate the wavelength of the present light source and the wavelength of the neighboring light source, control is performed in such a manner that the center wavelength of the first optical filter 41 is shifted so that the wavelengths λ_1, λ_2 will fall within the filtering width W [(1) → (2) → (3) in Fig. 30]. Next, the light source of wavelength λ_2 also emits light in addition to the light source of λ_1 and then the light source of λ_1 is extinguished [(3) → (4)]. As a result, the wavelength of the main-signal light can be changed over to the side of longer wavelength without any interruption in light.

[0127] Fig. 31 is a diagram useful in describing control for changing over wavelength when the wavelength of the main-signal light is changed over to the side of shorter wavelength. In Fig. 31, W represents the wavelength filtering width of the first optical filter 41. If the zero-dispersion wavelength fluctuates toward the side of shorter wavelength and changes to a wavelength intermediate the wavelength of the present light source and the wavelength of the neighboring light source, control is performed in such a manner that the center wavelength of the first optical filter 41 is shifted so that the wavelengths λ_0, λ_1 will fall within the filtering width W [(1) → (2) → (3) in Fig. 31]. Next, the light source of wavelength λ_0 also emits light in addition to the light source of λ_1 and then the light source of λ_1 is extinguished [(3) → (4)]. As a result, the wavelength of the main-signal light can be changed over to side of shorter wavelength without any interruption in light.

[0128] Fig. 32 is a diagram useful in describing the range of filtering width of the first optical filter 41. The filtering width W is a range which satisfies the following equation, where $\Delta\lambda$ represents the wavelength spacing of the light sources, τ represents the spectrum width and four-wave mixing is taken into account:

$$\Delta\lambda + \tau < W < 3\Delta\lambda - \tau \tag{5}$$

where $\Delta\lambda > \tau$

If this range is illustrated diagrammatically, it will be the hatched range bounded by the straight lines in Fig. 32. This is the range of filtering width when the spectrum width is equal to 1 nm (signal light 40 Gbps × 3 = 120G - 1 nm).

[0129] Figs. 33A and 33B are diagrams useful in describing wavelength relationship between monitoring light and main-signal light. In the embodiment of Fig. 28, the main-signal light and the monitoring light is described as being light generated by three neighboring light sources (see Fig. 33A). However, the wavelengths of the main-signal light and monitoring light need not be adjacent, for light from light sources spaced apart from the light source of the main-signal light can also be used as monitoring light, as shown in Fig. 33B. Further, wavelengths of light spaced sufficiently away from the wavelength of the main-signal light can be used as the wavelengths of the monitoring light in such a manner that four-wave mixing will not take place. In this case, however, the direction of fluctuation of the zero-dispersion wavelength cannot be detected according to the principle described in conjunction with Figs. 27A and 27B. The amount of wavelength dispersion, therefore, is calculated by a different method. It should be noted that four-wave mixing is a phenomenon in which light having a frequency different from that of the input light is produced.

[0130] Fig. 34 is a diagram showing the construction of an optical transmission system in which dispersion compensation is controlled by measuring the amount of wavelength dispersion using light of a wavelength sufficiently remote from the wavelength of the main-signal light, and Figs. 35A to 35C are diagrams useful in describing the fundamentals for calculating amount of wavelength dispersion. Shown in Fig. 34 are the optical transmitter 10, the optical receiver 20, the outgoing optical transmission line 30, a light multiplexer 31, a dispersion monitor 80 for detecting the wavelength (zero-dispersion wavelength) for the transmission characteristic is optimum in regard to the wavelength dispersion exhibited by the optical transmission line, the incoming optical transmission line 50, the dispersion monitoring signal transmitter 51 for transmitting the result of dispersion monitoring, and the dispersion monitoring signal receiver 52 for extracting the result of monitoring and inputting the result to the optical transmitter 10.

[0131] The optical transmitter 10 includes the plurality of light sources 11_1 - 11_n having different wavelengths (λ_1 - λ_n), the multiplexer 12, the external modulator 12b, and the output wavelength controller 13 for causing prescribed ones of the light sources 11_1 - 11_n to emit light, thereby changing the wavelength of the light output to the optical transmission line, and outputting light of the optimum wavelength to the optical transmission line based upon the result of detection by the dispersion monitor 80.

[0132] The dispersion monitor 80 includes a semiconductor laser for generating light of wavelength λ; a pulse generator 82 for generating pulses of pulse width d; a Mach-Zehnder modulator 83; a driver 84 for applying a drive voltage of $2V\pi$ across both electrodes of the Mach-Zehnder modulator 83 for the duration of the pulse width d; an optical detector 85 for detecting light of wavelength $\lambda \pm \Delta\lambda$; and a calculation unit 86 for calculating amount of wavelength dispersion. The zero-dispersion wavelength can be obtained from the amount of wavelength dispersion.

[0133] The Mach-Zehnder modulator 83 ordinarily performs data modulation by a drive voltage $V\pi$. However, by performing modulation by the drive voltage $2V\pi$, which is twice as large, short pulses can be generated at the rising edge [(1) in Fig. 35A] of the driving waveform and at the falling edge [(3) in Fig. 35A] of the driving waveform. Further, with the Mach-Zehnder modulator 83, chirping (wavelength fluctuation) $\Delta\lambda$ is proportional to the value of the differential of drive voltage Vin. Consequently, the sign of chirping at the rising edge [(1) in Fig. 35A] of the driving waveform is the opposite of that at the falling edge [(3) in Fig. 35A], and the two short pulses that are generated have different wavelengths, namely $\lambda + \Delta\lambda$ and $\lambda - \Delta\lambda$, respectively. If the Mach-Zehnder modulator 83 is driven by the driving drive signal Vin having the wavelength shown in Fig. 35B, the wavelength of the generated pulse on the side of the rising edge can be set to $\lambda + \Delta\lambda$ (where λ represents the center wavelength of the light source) and the wavelength of the generated pulse on the side of the falling edge can be set to $\lambda - \Delta\lambda$. If the Mach-Zehnder modulator 83 is driven by the driving drive signal Vin having the wavelength shown in Fig. 35C, the wavelength of the generated pulse on the side of the falling edge can be set to $\lambda - \Delta\lambda$ and the wavelength of the generated pulse on the side of the rising edge can be set to $\lambda + \Delta\lambda$.

[0134] Thus, since the two short pulses generated by the semiconductor laser 81 and Mach-Zehnder modulator 83 have mutually different wavelengths, a spread Δd ($d \rightarrow d + \Delta d$) is produced in the pulse interval after transmission owing to the group delay difference. Accordingly, it is possible to ascertain the value of dispersion exhibited by the optical transmission line by detecting the spread Δd. The spread Δd is represented by the following equation:

$$\begin{aligned}\Delta d(\mathrm{ps}) = {} & [\text{wavelength dispersion } D\ (\mathrm{ps/nm/km}) \text{ of transmission line}] \\ & \times [\text{transmission distance } L\ (\mathrm{km})] \times \Delta\lambda c\ (\mathrm{nm})\end{aligned} \tag{6}$$

(where $\Delta\lambda c$: $\Delta\lambda$ of pulse peak portion)

If the spread Δd is found, the wavelength dispersion D of the transmission line can be calculated from the above equation and the zero-dispersion wavelength can be obtained from the wavelength dispersion D.

[0135] The dispersion monitoring signal transmitter 51 sends this zero-dispersion wavelength to the optical transmitter and the output wavelength controller 13 changes over the light source of the main-signal light when the zero-dispersion wavelength becomes equal to a wavelength intermediate the wavelengths of the neighboring light sources.

[0136] In the embodiment shown in Fig. 34, the receiver is provided with the unit 86 for calculating the amount of wavelength dispersion. However, as shown in Fig. 36, it is possible to adopt an arrangement in which the transmitting side is provided with the calculation unit 86, two short pulses of different wavelengths are sent from the receiving side to the transmitting side, and wavelength dispersion D and zero-dispersion wavelength are calculated on the transmitting side.

[0137] The embodiment of Fig. 28 is for a case where use is made of an optical transmitter in which light is emitted solely from the necessary light source. However, it is also possible to use a transmitter in which all light sources emit light constantly and light having a desired wavelength is output to the optical transmission line through use of a light attenuator. Fig. 37 is a diagram showing the construction of such an arrangement using light attenuators. By turning off light attenuators 14_1 - 14_n provided between the light sources 11_1 - 11_n and multiplexer 12, light from a light source corresponding to a light attenuator that has been turned off can be output to the optical transmission line 30. Accordingly, by normally turning off the light attenuator of a light source that generates main-signal light, suitably turning off the light attenuator of a light source that generates monitoring light, multiplexing the light from these light sources and outputting the multiplexed light to the optical transmission line, dispersion compensation can be carried out by changing over the wavelength of the output light in a manner similar to that of Fig. 28.

[0138] Further, it is possible to use a transmitter in which all light sources normally emit light and light of a desired wavelength is output to the optical transmission line by a variable-wavelength filter. Fig. 38 is a diagram showing the construction of such an arrangement using variable-wavelength filters. By passing main-signal light and monitoring light via variable-wavelength filters 15', 15", respectively, provided at the output of the multiplexer 12, dispersion compensation can be carried out by changing over the wavelength of the output light in a manner similar to that of Fig. 28.

[0139] There are cases where beats are produced between light signals of mutually adjacent wavelengths, such as between main-signal light and monitoring light, as a result of which wavelength dispersion monitoring cannot be performed correctly on the receiving side owing to the influence of beat. Accordingly, if the polarizations of the two transmitted optical signals (the main-signal light and monitoring light) are made orthogonal, the occurrence of beat can be prevented and the precision of wavelength-dispersion monitoring can be improved.

[0140] Fig. 39 is a diagram showing an embodiment in which main-signal light and monitoring light are rendered orthogonal. Components identical with those of the embodiment shown in Fig. 28 are designated by like reference characters. This embodiment differs in terms of the construction of the optical transmitter 10. The optical transmitter 10 includes the plurality of light sources 11_1 - 11_n (discrete semiconductor lasers or semiconductor array laser) of different wavelengths (λ_1 - λ_n), the multiplexer 12, the external modulator 12b and the output wavelength controller 13. (1) Before the optical transmission system starts operating, the output wavelength controller 13 causes prescribed light sources 11_1 - 11_n to emit light, thereby changing the wavelength of light output to the optical transmission line. (2) When the system is in operation, the output wavelength controller 13 causes main-signal light and monitoring light to be output to the optical transmission line based upon the result of monitoring dispersion. (3) When the system is in operation, the output wavelength controller 13 causes the polarizations of the main-signal light and monitoring light to become orthogonal. Polarization controllers 18_1 - 18_n control directions of polarization of light output from the corresponding light sources in accordance with a command from the output wavelength controller 13. Polarization maintaining fibers 19a - 19b maintain the polarization of light applied thereto.

[0141] The output wavelength controller 13 causes light to be emitted from the light source of the main-signal light and the light source of the monitoring light and instructs the polarization controllers corresponding to these light sources to render the polarizations of the main-signal light and monitoring light orthogonal. As a result, the polarization controllers perform an adjustment in such a manner that the polarizations of the main-signal light and monitoring light are rendered orthogonal. These light beams are transmitted to the optical transmission line via the polarization maintaining fibers 19a, multiplexer 12, polarization maintaining fiber 19b and external modulator 12b. Since the polarizations are orthogonal, beat products are not produced and the precision of wavelength-dispersion monitoring can be improved. The system is effective as a short-distance transmission system in which the transmission line has a length of tens of kilometers.

(f) Embodiment in which wavelength dispersion is compensated for using monitoring light

[0142] Figs. 27A, 27B illustrate a case where a characteristic in which the intensity of a specific frequency component versus wavelength is approximated by a curve of second degree. Owing to the symmetry of the curve of second degree, the fact that zero-dispersion wavelength has changed to a wavelength intermediate the wavelength λ_1 of the main-signal light and the wavelength λ_2 of the monitoring light is detected when the intensity of a specific frequency component at wavelength λ_1 and the intensity of the specific frequency component at wavelength λ_2 have become equal.

[0143] However, there are instances where the characteristic of the intensity of a specific frequency component cannot be approximated by a curve of second degree. If the optical modulation scheme is NRZ modulation, for example, the characteristic of 40-GHz component intensity does not have left-right symmetry with respect to the zero-dispersion wavelength. Consequently, if λs_1 and λs_2 represent the wavelengths of the main-signal light and monitoring light, respectively, the monitoring component intensities $I(\lambda s_1)$, $I(\lambda s_2)$ at the wavelengths λs_1, λs_2 will have a certain ratio and will not be equal, as shown in Fig. 40C, even if the zero-dispersion wavelength is moved to the two wavelength centers. For example, when the light-source wavelength spacing is 3.2 nm ($= \lambda s_2 - \lambda s_1$) after transmission over an NRZ DSF of 100 km, the monitoring-component intensity ratio $I(\lambda s_1):I(\lambda s_2)$ is 1:1.6, where the α parameter is equal to -0.7. If the α parameter is equal to +0.7, then $I(\lambda s_1):I(\lambda s_2) = 1.6:1$ will hold. Thus, in a case where the characteristic of the intensity of a specific frequency component cannot be approximated by a curve of second degree, the intensity ratio $I(\lambda s_1):I(\lambda s_2)$ is detected and set by control software or is set from a control terminal. Thereafter, fluctuation of the monitored value at the wavelengths λs_1, λs_2 with the passage of time is sensed and the fact that the intensity ratio $I(\lambda s_1):I(\lambda s_2)$ has become equal to the above-mentioned set intensity ratio is detected. If the two become equal, then the zero-dispersion wavelength is $(\lambda s_2 + \lambda s_1)/2$. At the moment the two become equal, the monitoring light is changed over to the main-signal light and the main-signal light to the monitoring light.

[0144] Fig. 40A shows a relative delay-time characteristic, and Fig. 40B illustrates a power-penalty characteristic. It is necessary to decide the light-source wavelength spacing $\lambda s_2 - \lambda s_1$ in such a manner that the power penalty falls below 1 dB within the range λs_1 to λs_2.

[0145] Fig. 41 is a diagram showing the configuration of an optical transmission system according to this embodiment. Components in Fig. 41 identical with those shown in Fig. 28 are designated by like reference characters. This arrangement differs from that of Fig. 23 in the following respects:

(1) light attenuators 14_1 - 14_n are provided between the light sources 11_1 - 11_n and multiplexer 12 and prescribed ones thereof are turned on and off, whereby light from a light source corresponding to a light attenuator that has been turned off can be output to the optical transmission line 30 via the multiplexer 12 and external modulator 12b;
(2) the structure of wavelength-dispersion monitors 43, 44 is clearly shown; and
(3) a 40-GHz signal generator 46 is added on for generating a 40-GHz synchronized to the bit rate required for the optical receiver 20.

[0146] By providing the light attenuators 14_1 - 14_n, the light attenuator of the light source that generates the main-signal light can be turned off at all times, the light attenuator of the light source that generates the monitoring light can be turned off when appropriate and the light from these light sources can be combined and output to the optical transmission line 30. In other words, by turning off a prescribed light attenuator, the wavelengths of the main-signal light and monitoring light can be changed over to control dispersion compensation. The wavelength-dispersion monitors 43, 44 respectively include light-receiving devices 43a, 44a such as photodiodes for converting light, which has been branched from the optical transmission line 30, to electric signals; band-pass filters (BPF) 43b, 44b having a specific frequency (40 GHz) as their center frequencies; amplifiers 43c, 44c, and power meters 43d, 44d for detecting the power of the specific frequency component (40-GHz component). The 40-GHz signal generator 46 has a dispersion add-on unit 46a for dispersing the wavelength of light output by the filter 41 and outputting light that contains the 40-GHz component, a light-receiving device 46b such as a photodiode for converting light, which is output by the dispersion add-on unit 46a, to an electric signal, and a band-pass filter (BPF) 46c having 40 GHz as the center frequency.

[0147] Fig. 42 shows the flow of processing for wavelength dispersion compensation (initial setting) before the start of system operation. Before the system is started up, the output wavelength controller 13 opens and closes the light attenuators 14_1 - 14_n in order. The dispersion compensation control unit 45 controls the wavelength of the optical filter 41 and reads in the 40-GHz component intensity, which is the measured value from the power meter 43d, while being operated in association with the opening and closing of the attenuators (step 201). The dispersion compensation control unit 45 plots the characteristic of the 40-GHz component intensity using this measured value (Fig. 43A; step 202). From the characteristic of the 40-GHz component intensity, the dispersion compensation control unit 45 obtains the wavelengths λ_2, λ_3 of two light sources bracketing the zero-dispersion wavelength λ for which the 40-GHz component intensity is minimized (step 203). It is assumed that the 40-GHz component intensity at wavelength λ_2 is smaller than that at wavelength λ_3.

[0148] Next, in accordance with a command from the dispersion compensation control unit 45, the output wavelength controller 13 opens the light attenuators 14_2, 14_3 corresponding to the wavelengths λ_2, λ_3, and the dispersion compensation control unit 45 sets the wavelength λ_2 as the center wavelength of the first optical filter 41 and the wavelength λ_3 as the center wavelength of the second optical filter 42 (step 204).

[0149] Thus, the light of wavelength λ_2 nearest the zero-dispersion wavelength becomes the main-signal light and the light of wavelength λ_3 becomes the monitoring light, where the wavelengths λ_2, λ_3 ($\lambda_2 < \lambda_3$) bracket the zero-dispersion wavelength.

[0150] Fig. 44 shows the flow of processing for wavelength dispersion compensation in a case where zero-dispersion wavelength moves toward the long-wavelength side. Before the system starts operating, the dispersion compensation control unit 45 obtains, from the characteristic of the 40-GHz component intensity, the 40-GHz component intensity ratio $I(\lambda_2):I(\lambda_3)$ for changing over the main-signal light (step 211). The intensity ratio is assumed to be 1:1.6.

[0151] Next, during system operation, the dispersion compensation control unit 45 reads in the 40-GHz component intensities $I(\lambda_2)$, $I(\lambda_3)$ of the wavelengths λ_2, λ_3 from the power meters 43d, 44d (step 212), checks the increase or decrease in the 40-GHz component intensities $I(\lambda_2)$, $I(\lambda_3)$ from one sampling earlier and identifies movement of the zero-dispersion wavelength (step 213).

[0152] If $I(\lambda_2)$ is increasing and $I(\lambda_3)$ decreasing in case of movement (see Fig. 43B), it is judged that the zero-dispersion wavelength λ is between λ_2 and λ_3 and is moving toward the side of longer wavelength (step 214). Next, $I(\lambda_2)$ is multiplied by 1.6 to effect a correction $[I(\lambda_2) \times 1.6 \rightarrow I(\lambda_2)]$, and $I(\lambda_2)$ after correction is compared with $I(\lambda_3)$ in terms of magnitude (step 215).

[0153] If $I(\lambda_2) < I(\lambda_3)$ holds, then processing from step 212 onward is repeated. If $I(\lambda_2) = I(\lambda_3)$ holds (step 216), the main-signal light is changed over. That is, the monitoring light of wavelength λ_3 is changed over to the main-signal light and the main-signal light of wavelength λ_2 is changed over to the monitoring light. The procedure for making this change is described below.

[0154] If, after the main-signal light is changed, the zero-dispersion wavelength λ moves further toward the side of longer wavelength, $I(\lambda_2)$ increases and so does $I(\lambda_3)$, then the zero-dispersion wavelength λ becomes longer than the wavelength λ_3 of the main-signal light and the relation $\lambda_3 < \lambda < \lambda_4$ is established (see Fig. 43C; step 217). If $\lambda_3 < \lambda < \lambda_4$ holds, then the light of light-source wavelength λ_4 is changed over to the monitoring light (see Fig. 43D; step 218). Processing from step 212 onward is then repeated. When the monitoring light is changed over, the light attenuator 14_1 is opened and the light attenuator 14_3 is closed to set the wavelength λ_4 as the center wavelength of the second optical filter 42.

[0155] Fig. 45 shows the flow of processing for controlling changeover of the main-signal light, and Fig. 46 is a diagram useful in describing control for changing over the main-signal light.

[0156] If $I(\lambda_2) = I(\lambda_3)$ holds (step 216 in Fig. 44), the monitoring light of wavelength λ_3 is changed over to main-signal light and the main-signal light of wavelength λ_2 is changed over to monitoring light.

[0157] First, the light attenuator 14_3 is closed (step 221; state a in Fig. 44). Next, the center wavelength of the first optical filter 41 is shifted toward the side of longer wavelength and control is performed in such a manner that the wavelengths λ_2, λ_3 fall within the filter range W (step 222, states b, c). In state c, the light attenuator 14_3 is opened gradually and then the light attenuator 14_2 is closed gradually in order to prevent instantaneous interruption of signal (steps 223 - 225; states d - f). It is important that the light attenuator 14_3 is first opened. If the light attenuator 14_2 is first closed, there is the danger that instantaneous interruption of light will occur. If the light attenuator 14_2 is closed fully (state g), the center wavelength of the first optical filter 41 is shifted to λ_3 (step 226; state h). This completes changeover of the main-signal light (step 227). Finally, the light attenuator 14_2 is opened and λ_2 is set as the center wavelength of the second optical filter 42 (step 228; state i). Thus, the main-signal light can be changed over while the power of the light is held constant.

[0158] Figs. 47A to 47C are diagrams useful in describing the results of experiments in a case where monitoring light of wavelength λ_2 is changed over to main-signal light and main-signal light of wavelength λ_1 is changed over to monitoring light. Fig. 47A illustrates the characteristics of received-light powers $P(\lambda_1)$, $P(\lambda_2)$ of wavelengths λ_1, λ_2 and the characteristic of total power P_{total}, as well as the characteristic of reception sensitivity. Fig. 47B illustrates eye patterns at the start of changeover (A), during changeover (B) and after changeover (C). Fig. 47C shows characteristics of light intensity versus wavelength at the start of changeover (A), during changeover (B) and after changeover (C). It will be understood from Fig. 47A that changeover of the main-signal light can be performed by holding the penalty below 1 dB, and it will be appreciated from Fig. 47B that changeover of the main-signal light can be performed without degradation of the eye patterns.

[0159] Fig. 48 shows the flow of processing for wavelength dispersion compensation in a case where zero-dispersion wavelength moves toward the short-wavelength side, and Figs. 49A to 49D are views useful in describing this processing.

[0160] Prior to the start of system operation, the light of wavelength λ_3 nearest the zero-dispersion wavelength is set to the main-signal light and the light of wavelength λ_2 is set to the monitoring light by the initial setting processing of Fig. 42, where the wavelengths λ_2, λ_3 ($\lambda_2 < \lambda_3$) bracket the zero-dispersion wavelength.

[0161] Prior to system operation, the dispersion compensation control unit 45 obtains, from the characteristic of the 40-GHz component intensity (see Fig. 49A), the 40-GHz component intensity ratio $I(\lambda_2):I(\lambda_3)$ for changing over the main-signal light (step 251). The intensity ratio is assumed to be 1:1.6.

[0162] Next, during system operation, the dispersion compensation control unit 45 reads in the 40-GHz component intensities $I(\lambda_2)$, $I(\lambda_3)$ of the wavelengths λ_2, λ_3 from the power meters 43d, 44d (step 252), checks the increase or decrease in the 40-GHz component intensities $I(\lambda_2)$, $I(\lambda_3)$ from one sampling earlier and identifies movement of the zero-dispersion wavelength (step 253).

[0163] If $I(\lambda_2)$ is decreasing and $I(\lambda_3)$ increasing in case of movement (see Fig. 49B), it is judged that the zero-dispersion wavelength λ is between λ_2 and λ_3 and is moving toward the side of shorter wavelength (step 254). Next, $I(\lambda_2)$ is multiplied by 1.6 to effect a correction $[I(\lambda_2) \times 1.6 \rightarrow I(\lambda_2)]$, and $I(\lambda_2)$ after correction is compared with $I(\lambda_3)$ in terms of magnitude (step 255).

[0164] If $I(\lambda_2) > I(\lambda_3)$ holds, then processing from step 252 onward is repeated. If $I(\lambda_2) = I(\lambda_3)$ holds (step 256), the main-signal light is changed over. That is, the monitoring light of wavelength λ_2 is changed to the main-signal light and the main-signal light of wavelength λ_3 is change to the monitoring light. The procedure for making this change is described below.

[0165] If, after the main-signal light is changed, the zero-dispersion wavelength λ moves further toward the side of shorter wavelength, $I(\lambda_2)$ increases and so does $I(\lambda_3)$, then the zero-dispersion wavelength λ becomes shorter than the wavelength λ_2 of the main-signal light and the relation $\lambda_1 < \lambda < \lambda_2$ is established (see Fig. 49C; step 257). If $\lambda_1 < \lambda < \lambda_2$

holds, then the light of light-source wavelength λ_1 is changed over to the monitoring light (see Fig. 49D; step 258). Processing from step 252 onward is then repeated. When the monitoring light is changed over, the light attenuator 14_1 is opened and the light attenuator 14_3 is closed to set the wavelength λ_1 as the center wavelength of the second optical filter 42.

[0166] Fig. 50 shows the flow of processing for controlling changeover of main-signal light in a case where zero-dispersion wavelength is moving toward the short-wavelength side, and Fig. 51 is a diagram useful in describing control for changing over the main-signal light.

[0167] If $I(\lambda_2) = I(\lambda_3)$ holds (step 256 in Fig. 48), the monitoring light of wavelength λ_2 is changed over to main-signal light and the main-signal light of wavelength λ_3 is changed over to monitoring light.

[0168] First, the light attenuator 14_2 is closed (step 271; state a in Fig. 51). Next, the center wavelength of the first optical filter 41 is shifted toward the side of shorter wavelength and control is performed in such a manner that the wavelengths λ_2, λ_3 fall within the filter range W (step 272, states b, c). In state c, the light attenuator 14_2 is opened gradually and then the light attenuator 14_3 is closed gradually in order to prevent instantaneous interruption of signal (steps 273 - 275; stated d - f). If the light attenuator 14_3 is closed fully (state g), the center wavelength of the first optical filter 41 is shifted to λ_2 (step 276; state h). This completes changeover of the main-signal light (step 277). Finally, the light attenuator 14_3 is opened and λ_3 is set as the center wavelength of the second optical filter 42 (step 278). Thus, the main-signal light can be changed over while the power of the light is held constant.

[0169] Figs. 52A and 52B are diagrams of 40-GHz component intensity characteristics for respective modulation schemes when modulation has been performed by 40-GHz data, in which Fig. 52A is a characteristic diagram for OTDM modulation and Fig. 52B a characteristic diagram for RZ modulation. In case of OTDM modulation, the zero-dispersion wavelength is one where the characteristic indicates a minimum value at the center of two peaks. The characteristic in the vicinity of the zero-dispersion wavelength can be approximated by a curve of second degree whose summit is indicated at the zero-dispersion wavelength. Owing to the symmetry of the curve of second degree, the fact that zero-dispersion wavelength has changed to a wavelength intermediate the wavelength λ_1 of the main-signal light and the wavelength λ_2 of the monitoring light can be detected when the intensity of the 40-GHz component at wavelength λ_1 and the intensity of the 40-GHz component at wavelength λ_2 have become equal.

[0170] In case of RZ modulation, the zero-dispersion wavelength is one where the characteristic indicates a maximum value. The characteristic in the vicinity of the zero-dispersion wavelength can be approximated by a curve a second degree whose summit is indicated at the zero-dispersion wavelength. Owing to the symmetry of the curve of second degree, the fact that zero-dispersion wavelength has changed to a wavelength intermediate the wavelength λ_1 of the main-signal light and the wavelength λ_2 of the monitoring light can be detected when the intensity of the 40-GHz component at wavelength λ_1 and the intensity of the 40-GHz component at wavelength λ_2 have become equal.

(g) First embodiment for controlling main-signal light by detecting a wavelength for which the intensity of a specific frequency component indicates the maximum value

[0171] In the case described above, the zero-dispersion wavelength for which the intensity of a specific frequency component indicates the minimum value is detected and wavelength dispersion is controlled by using, as main-signal light and monitoring light, two light-source wavelengths bracketing the zero-dispersion wavelength. It should be noted that the power penalty can be made less than 1 dB even if the wavelength of light sent to the optical transmission line is decided such that the intensity of a specific frequency component (the 40-GHz component) takes on the maximum value, as evident from Fig. 53. Accordingly, this embodiment obtains two light-source wavelengths λ_2, λ_3 ($\lambda_2 < \lambda_3$) bracketing a wavelength for which the intensity of the 40-GHz component is maximized, adopts the wavelength of light for which the intensity of the 40-GHz component is larger as the main-signal light and adopts the light of the other wavelength as the monitoring light.

[0172] The characteristic in the vicinity of the wavelength for which intensity is maximized can be approximated by a curve of second degree. Owing to the symmetry of the curve of second degree, the fact that wavelength for which intensity is maximized has changed to a wavelength intermediate the wavelength λ_2 of the main-signal light and the wavelength λ_3 of the monitoring light can be detected when the intensity of the 40-GHz component contained in the light of wavelength λ_2 and the intensity of the 40-GHz component contained in the light of wavelength λ_3 have become equal.

[0173] The direction in which the zero-dispersion wavelength fluctuates, i.e., the direction of fluctuation of the wavelength for which intensity is maximized, can be obtained based upon the increase or decrease in the intensities $I(\lambda_2)$, $I(\lambda_3)$ at the light-source wavelengths λ_2, λ_3, respectively. More specifically, (1) when the wavelength λ_m for which intensity is maximum fluctuates toward the side of longer wavelength, the monitoring component intensity $I(\lambda_2)$ of the wavelength λ_2 of main-signal light decreases and the monitoring component intensity $I(\lambda_3)$ of the wavelength λ_3 of monitoring light increases, as shown in Fig. 54A. (2) when the wavelength λ_m for which intensity is maximum fluctuates further toward the side of longer wavelength and exceeds the wavelength $\lambda 3$, both $I(\lambda_2)$ and $I(\lambda_3)$ decrease, as shown in Fig. 54B. (3) when the wavelength λ_m for which intensity is maximum fluctuates toward the side of shorter wavelength, on the other hand, the monitoring component intensity I(λ_2) of the wavelength λ_2 of monitoring light increases and the monitoring component intensity I(λ_3) of the wavelength λ_3 of main-signal light decreases, as shown in Fig. 54D. When the wavelength λ_m for which intensity is maximum fluctuates further toward the side of shorter wavelength and becomes shorter than the wavelength $\lambda 2$, both I(λ_2) and I(λ_3) decrease, as shown in Fig. 54E.

- Control when wavelength for which intensity is maximum fluctuates toward side of longer wavelength

[0174] In the optical transmission system of Fig. 41, control is such that prior to system operation, the two light-source wavelengths λ_2, λ_3 ($\lambda_2 < \lambda_3$) that bracket the wavelength λ_m for which the monitoring component intensity is maximized are obtained, the light of wavelength λ_2 for which the monitoring component intensity is larger is adopted as main-signal light and the light of wavelength λ_3 is adopted as monitoring light. If, during system operation, the wavelength of maximum intensity fluctuates toward the side of longer wavelength and the relation $I(\lambda_2) = I(\lambda_3)$ is established, then the monitoring light of wavelength λ_3 is changed over to the main-signal light and the main-signal light of wavelength λ_2 is changed over to the monitoring light. If the wavelength of maximum intensity fluctuates further toward the side of longer wavelength and both I(λ_2) and I(λ_3) decrease (see Fig. 54B), then the light of wavelength λ_4 instead of wavelength λ_2 is made the monitoring light (see Fig. 54C).

- Control when wavelength for which intensity is maximum fluctuates toward side of shorter wavelength

[0175] In the optical transmission system of Fig. 41, the two light-source wavelengths λ_2, λ_3 ($\lambda_2 < \lambda_3$) that bracket the wavelength λ_m for which the monitoring component intensity is maximized are obtained, the light of wavelength λ_3 for which the monitoring component intensity is larger is adopted as main-signal light and the light of wavelength λ_2 is adopted as monitoring light. If, during system operation, the wavelength of maximum intensity fluctuates toward the side of shorter wavelength and the relation $I(\lambda_2) = I(\lambda_3)$ is established, then the monitoring light of wavelength λ_2 is changed over to the main-signal light and the main-signal light of wavelength λ_3 is changed over to the monitoring light. If the wavelength of maximum intensity fluctuates further toward the side of shorter wavelength and both I(λ_2) and I(λ_3) decrease (see Fig. 54E), then the light of wavelength λ_1 instead of wavelength λ_3 is made the monitoring light (see Fig. 54F).

(h) Second embodiment for controlling main-signal light by detecting a wavelength for which the intensity of a specific frequency component indicates the maximum value

[0176] In the first embodiment described above, the zero-dispersion wavelength for which the intensity of a specific frequency component indicates the maximum value is detected and wavelength dispersion is controlled by using, as main-signal light and monitoring light, two light-source wavelengths bracketing the zero-dispersion wavelength. As shown in Fig. 55, let $\Delta\lambda$ represent the difference in wavelength between the wavelength λ_m for which the intensity of a specific frequency component indicates the maximum value and the zero-dispersion wavelength λ for which the intensity of the specific frequency component indicates the minimum value. If the characteristic of the specific frequency component is shifted leftward by $\Delta\lambda$, the result will be as indicated by the dotted line in Fig. 55. In accordance with the shifted characteristic, the wavelength indicating the wavelength of maximum intensity is the zero-dispersion wavelength. Since the characteristic in the vicinity of the zero-dispersion wavelength is a curve of second degree, wavelength dispersion can be compensated for in accurate fashion.

[0177] According to the second embodiment, therefore, control is carried out in such a manner that the wavelength for which the intensity of a specific frequency component indicates the maximum value is detected and light of the zero-dispersion wavelength is sent to the optical transmission line.

[0178] Fig. 56 is a diagram showing the configuration of an optical transmission system in which main-signal light is changed over by detecting a wavelength for which intensity is maximum. Components in Fig. 56 identical with those of the optical transmission system shown in Fig. 41 are designated by like reference characters. This arrangement differs from that of Fig. 41 in that dispersion-add on units 47, 48, which furnish received light with wavelength dispersion conforming to the wavelength difference $\Delta\lambda$ between the wavelength λ_m for which intensity is maximum and the zero-dispersion wavelength, are provided on the output sides of the first and second optical filters 41, 42, respectively. By virtue of the dispersion-add on units 47, 48, the wavelength of light output by the first optical filter 41 set to the wavelength λ_2 of main-signal light becomes ($\lambda_2 + \Delta\lambda$), the wavelength of light output by the second optical filter 42 set to the wavelength λ_3 of monitoring light becomes ($\lambda_3 + \Delta\lambda$) and the wavelength λ_m of maximum intensity resides between these two wavelengths.

•Control when wavelength for which intensity is maximum fluctuates toward side of longer wavelength

[0179] Control is such that prior to system operation, the wavelength λ_m for which the monitoring component intensity is maximized is detected, the two light-source wavelengths λ_2, λ_3 ($\lambda_2 < \lambda_3$) that bracket the zero-dispersion wavelength(λ_m - $\Delta\lambda$) are obtained, the light of wavelength λ_2 for which the monitoring component intensity is smaller is adopted as main-signal light and the light of wavelength λ_3 is adopted as monitoring light. If, during system operation, the zero-dispersion wavelength fluctuates toward the side of longer wavelength and the relation $I(\lambda_2 + \Delta\lambda) = I(\lambda_3 + \Delta\lambda)$ is established, then the monitoring light of wavelength λ_3 is changed over to the main-signal light and the main-signal light of wavelength λ_2 is changed over to the monitoring light. If the zero-dispersion wavelength fluctuates further toward the side of longer wavelength and both $I(\lambda_2 + \Delta\lambda)$ and $I(\lambda_3 + \Delta\lambda)$ decrease, then the light of wavelength λ_4 instead of wavelength λ_2 is made the monitoring light.

•Control when wavelength for which intensity is maximum fluctuates toward side of shorter wavelength

[0180] Control is such that prior to system operation, the wavelength λ_m for which the monitoring component intensity is maximized is detected, the two light-source wavelengths λ_2, λ_3 ($\lambda_2 < \lambda_3$) that bracket the zero-dispersion wavelength(λ_m - $\Delta\lambda$) are obtained, the light of wavelength λ_3 for which the monitoring component intensity is smaller is adopted as main-signal light and the light of wavelength λ_2 is adopted as monitoring light. If, during system operation, the zero-dispersion wavelength fluctuates toward the side of shorter wavelength and the relation $I(\lambda_2 + \Delta\lambda) = I(\lambda_3 + \Delta\lambda)$ is established, then the monitoring light of wavelength λ_2 is changed over to the main-signal light and the main-signal light of wavelength λ_3 is changed over to the monitoring light. If the zero-dispersion wavelength fluctuates further toward the side of shorter wavelength and both $I(\lambda_2 + \Delta\lambda)$ and $I(\lambda_3 + \Delta\lambda)$ decrease, then the light of wavelength λ_1 instead of wavelength λ_3 is made the monitoring light.

[0181] Fig. 57 is a diagram showing another configuration of an optical transmission system in which main-signal light is changed over by detecting a wavelength for which intensity is maximum. Components in Fig. 57 identical with those of the optical transmission system shown in Fig. 56 are designated by like reference characters. This arrangement differs from that of Fig. 56 in that the 40-GHz signal generator 46 is eliminated and the 40-GHz signal is input to the optical receiver 20 from the bandpass filter 43b.

(i) Embodiment for detecting a wavelength for which the intensity of a specific frequency component indicates the minimum value and sending an optical transmission line main-signal light for which the intensity of the specific frequency component is maximized

[0182] In the embodiment of Fig. 53, the wavelength λm for which the intensity of the specific frequency component is maximized is detected and light having the light-source wavelength for which the intensity of the specific frequency component is maximized is sent to the optical transmission line as the main-signal light. As shown in Fig. 58, let $\Delta\lambda$ represent the difference in wavelength between the wavelength λ_m for which the intensity of a specific frequency component indicates the maximum value and the zero-dispersion wavelength λ for which the intensity of the specific frequency component indicates the minimum value. If the characteristic of the specific frequency component is shifted rightward by $\Delta\lambda$, the result will be as indicated by the dotted line in Fig. 55. In accordance with the shifted characteristic, the zero-dispersion wavelength is the wavelength of maximum intensity that prevailed prior to the shift.

[0183] According to this embodiment, therefore, control is carried out in such a manner that the zero-dispersion wavelength for which the intensity of a specific frequency component indicates the minimum value is detected and light of the wavelength λ_m of maximum intensity is sent to the optical transmission line. The configuration shown in Fig. 56 can be employed as the optical transmission system of this embodiment. However, the dispersion add-on units 47, 48 provide the output light of optical filters 41, 42 with wavelength dispersion conforming to -$\Delta\lambda$. As a result, the wavelength λ_2 of the main-signal light output by the first filter 41 becomes (λ_2 - $\Delta\lambda$), the wavelength λ_3 of light output by the second optical filter 42 set to the wavelength λ_3 of monitoring light becomes (λ_3 - $\Delta\lambda$) and the zero-dispersion wavelength resides between these two wavelengths.

•Control when zero-dispersion wavelength fluctuates toward side of longer wavelength

[0184] Control is such that prior to system operation, the zero-dispersion wavelength λ for which the monitoring component intensity is minimized is detected, the two light-source wavelengths λ_2, λ_3 ($\lambda_2 < \lambda_3$) that bracket the wavelength ($\lambda + \Delta\lambda$) of maximum intensity are obtained, the light of wavelength λ_2 for which the monitoring component intensity is larger is adopted as main-signal light and the light of wavelength λ_3 is adopted as monitoring light. If, during system operation, the wavelength for maximum intensity fluctuates toward the side of longer wavelength and the relation $I(\lambda_2 - \Delta\lambda) = I(\lambda_3 - \Delta\lambda)$ is established, then the monitoring light of wavelength λ_3 is changed over to the main-signal light and the main-signal light of wavelength λ_2 is changed over to the monitoring light. If the zero-dispersion wavelength fluctuates further toward the side of longer wavelength and both $I(\lambda_2 - \Delta\lambda)$ and $I(\lambda_3 - \Delta\lambda)$ increase, then the light of wavelength λ_4 instead of wavelength λ_2 is made the monitoring light.

•Control when wavelength of maximum intensity fluctuates toward side of shorter wavelength

[0185] Control is such that prior to system operation, the zero-dispersion wavelength λ for which the monitoring component intensity is minimized is detected, the two light-source wavelengths λ_2, λ_3 ($\lambda_2 < \lambda_3$) that bracket the wavelength ($\lambda + \Delta\lambda$) of maximum intensity are obtained, the light of wavelength λ_3 for which the monitoring component intensity is larger is adopted as main-signal light and the light of wavelength λ_2 is adopted as monitoring light. If, during system operation, the wavelength for maximum intensity fluctuates toward the side of shorter wavelength and the relation $I(\lambda_2 - \Delta\lambda) = I(\lambda_3 - \Delta\lambda)$ is established, then the monitoring light of wavelength λ_2 is changed over to the main-signal light and the main-signal light of wavelength λ_3 is changed over to the monitoring light. If the wavelength for which intensity is maximum fluctuates further toward the side of shorter wavelength and both $I(\lambda_2 - \Delta\lambda)$ and $I(\lambda_3 - \Delta\lambda)$ increase, then the light of wavelength λ_1 instead of wavelength λ_3 is made the monitoring light.

(j) Embodiment in a case where two waves are used as monitoring light

[0186] The foregoing is for a case where zero-dispersion wavelength is detected using two waves, namely main-signal light and monitoring light, and control is performed to change over main-signal light and monitoring light. In this embodiment, however, detection of zero-dispersion wavelength and control for changing over main-signal light and monitoring light are carried out using three waves, namely main-signal light and two monitoring light beams. Figs. 59A to 59D are diagrams useful in describing the principle of detection of zero-dispersion wavelength and control for changing over main-signal light and monitoring light using three waves.

[0187] Let λ_1, λ_2, λ_3 ($\lambda_1 < \lambda_2 < \lambda_3$) represent the wavelengths of the three waves of main-signal light and two monitoring light beams.

(1) If the zero-dispersion wavelength λ moves toward the size of longer wavelength so that $\lambda > \lambda_3$ holds (See Fig. 59A), the wavelength of the monitoring light is switched from λ_1 to λ_4.

(2) If the zero-dispersion wavelength λ falls within the range $\lambda_2 < \lambda < \lambda_3$ (see Fig. 59B) and becomes equal to $(\lambda_3 - \lambda_2)/2$, the monitoring light is changed over to the main-signal light and the main-signal light is changed over to the monitoring light. For example, if the zero-dispersion wavelength λ moves toward the side of longer wavelength and becomes equal to $(\lambda_3 - \lambda_2)/2$, the monitoring light of wavelength λ_3 is changed over to the main-signal light and the main-signal light of wavelength λ_2 is changed over to the monitoring light. If the zero-dispersion wavelength λ moves toward the side of shorter wavelength and becomes equal to $(\lambda_3 - \lambda_2)/2$, the monitoring light of wavelength λ_2 is changed over to the main-signal light and the main-signal light of wavelength λ_3 is changed over to the monitoring light.

(3) Similarly, if the zero-dispersion wavelength λ falls within the range $\lambda_1 < \lambda < \lambda_2$ (see Fig. 59C) and becomes equal to $(\lambda_2 - \lambda_1)/2$, the monitoring light is changed over to the main-signal light and the main-signal light is changed over to the monitoring light. For example, if the zero-dispersion wavelength λ moves toward the side of longer wavelength and becomes equal to $(\lambda_2 - \lambda_1)/2$, the monitoring light of wavelength λ_2 is changed over to the main-signal light and the main-signal light of wavelength λ_1 is changed over to the monitoring light. If the zero-dispersion wavelength λ moves toward the side of shorter wavelength and becomes equal to $(\lambda_2 - \lambda_1)/2$, the monitoring light of wavelength λ_1 is changed over to the main-signal light and the main-signal light of wavelength λ_2 is changed over to the monitoring light.

(4) If the zero-dispersion wavelength λ moves toward the side of shorter wavelength so that $\lambda < \lambda_1$ holds (see Fig. 59D), the wavelength of the monitoring light is changed over from λ_4 to λ_1.

[0188] Fig. 60 is a diagram showing the configuration of an optical transmission system in which wavelength dispersion is compensated for using three waves, namely main-signal light and two monitoring light beams. Components in Fig. 60 identical with those of the optical transmission system shown in Fig. 41 are designated by like reference characters. This arrangement differs from that of Fig. 41 in the following respects:

(1) three light attenuators are opened so that main-signal light and two beams of monitoring light from three adjacent light sources are combined and sent to the optical transmission line;

(2) a third optical filter 61 is provided and the wavelength of the second monitoring light is set as the center wavelength of this optical filter;

(3) a third dispersion monitor 62 is provided and measures the intensity of the 40-GHz component contained in the

second monitoring light; and

(4) the dispersion compensation control unit 45 controls changeover of the main-signal light and changeover of the monitoring light based upon the intensities of the 40-GHz component contained in the three waves, namely in the main-signal light and first and second monitoring light.

[0189] Fig. 61 shows the flow of processing for wavelength dispersion compensation (initial setting) prior to system operation in a case where three waves are used. Before the system is started up, the output wavelength controller 13 opens and closes the light attenuators 14_1 - 14_n in order. The dispersion compensation control unit 45 controls the wavelength of the optical filter 41 and reads in the 40-GHz component intensity, which is the measurement value from the power meter 43d, while being operated in association with the opening and closing of the attenuators (step 201). The dispersion compensation control unit 45 plots the characteristic of the 40-GHz component intensity using this measured value (step 302). The dispersion compensation control unit 45 then obtains the two light-source wavelengths λ_2 and λ_3, which bracket the zero-dispersion wavelength λ for which the intensity of the 40-GHz component is minimized, and the wavelength λ_1 for which the intensity of the 40-GHz component is small, reads in the intensities of the 40-GHz components of the three wavelengths λ_1 to λ_3 and compares the magnitudes of three read intensities of the 40-GHz components (step 303).

[0190] Next, in accordance with a command from the dispersion compensation control unit 45, the output wavelength controller 13 opens the two light attenuators that correspond to the wavelength (λ_2) for which the 40-GHz component intensity is smallest and the wavelength (λ_3) for which the 40-GHz component intensity is the second smallest, sets the wavelength λ_2 of the smallest value as the center wavelength of the first optical filter 41 and sets the wavelength λ_3 of the second smallest value as the center wavelength of the second optical filter 42 (step 304).

[0191] The output wavelength controller 13 opens the light attenuator corresponding to the wavelength λ_1 and sets the wavelength λ_1 as the center wavelength of the third optical filter 43 (step 305).

[0192] Fig. 62 shows the flow of processing for wavelength dispersion compensation after the start of system operation in a case where three waves are used. Before the system starts operating, the dispersion compensation control unit 45 obtains, from the characteristic of the 40-GHz component intensity, the 40-GHz component intensity ratio $I(\lambda_2):I(\lambda_3)$ for changing over the main-signal light (step 311). The intensity ratio is assumed to be 1:1.6.

[0193] Next, the dispersion compensation control unit 45 reads in the 40-GHz component intensities $I(\lambda_1)$, $I(\lambda_2)$, $I(\lambda_3)$ of the wavelengths λ_1, λ_2, λ_3 from the power meters 43d, 44d, 62d, respectively (step 312), compares these intensities in terms of magnitude and identifies movement of the zero-dispersion wavelength (step 313).

[0194] If the zero-dispersion wavelength λ moves toward the side of longer wavelength so that $I(\lambda_1) > I(\lambda_2) > I(\lambda_3)$ holds, then $\lambda > \lambda_3$ holds [Fig. 59(a); step 314). In such case the monitoring light is changed over from the light of light-source wavelength λ_1 to the light of light-source wavelength λ_4 (step 315). Processing from step 312 onward is then repeated. When the monitoring light is changed over, the light attenuator 14_4 is opened and the light attenuator 14_1 is closed to set the wavelength λ_4 as the center wavelength of the second optical filter 42.

[0195] If the zero-dispersion wavelength λ moves toward the side of shorter wavelength so that $I(\lambda_1) < I(\lambda_2) < I(\lambda_3)$ holds, then $\lambda < \lambda_1$ holds [Fig. 59(d); step 316). In such case the monitoring light is changed over from the light of light-source wavelength λ_4 to the light of light-source wavelength λ_1 (step 317). Processing from step 312 onward is then repeated. When the monitoring light is changed over, the light attenuator 14_4 is opened and the light attenuator 14_1 is closed to set the wavelength λ_4 as the center wavelength of the second optical filter 42.

[0196] If $I(\lambda_1) > I(\lambda_3) \geq I(\lambda_2)$ holds, on the other hand [see Fig. 59(b)], then the zero-dispersion wavelength λ satisfies the relation $\lambda_2 < \lambda < \lambda_3$ (step 318). If the zero-dispersion wavelength is between λ_2 and λ_3, then $I(\lambda_2)$ is multiplied by 1.6 to effect a correction $[I(\lambda_2) \times 1.6 \rightarrow I(\lambda_2)]$, and $I(\lambda_2)$ after correction is compared with $I(\lambda_3)$ in terms of magnitude (step 319).

[0197] If $I(\lambda_3) \neq I(\lambda_2)$ holds, processing from step 212 onward is repeated. If $I(\lambda_2) = I(\lambda_3)$ holds (step 320), then the main-signal light is changed over. That is, the monitoring light is changed over to the main-signal light and the main-signal light is changed over to the monitoring light. The procedure for making this change is described below.

[0198] If $I(\lambda_2) \leq I(\lambda_1) < I(\lambda_3)$ holds [see Fig. 59(c)], then the zero-dispersion wavelength λ satisfies the relation $\lambda_1 < \lambda < \lambda_2$ (step 321). If the zero-dispersion wavelength λ is between λ_1 and λ_2, then $I(\lambda_1)$ is multiplied by 1.6 to effect a correction $[I(\lambda_1) \times 1.6 \rightarrow I(\lambda_1)]$, and $I(\lambda_1)$ after correction is compared with $I(\lambda_2)$ in terms of magnitude (step 322).

[0199] If $I(\lambda_2) \neq I(\lambda_1)$ holds, processing from step 312 onward is repeated. If $I(\lambda_2) = I(\lambda_1)$ holds (step 323), then the main-signal light is changed over. That is, the monitoring light of wavelength λ_2 is changed over to the main-signal light and the main-signal light of wavelength λ_1 is changed over to the monitoring light.

[0200] The foregoing is for a case where the zero-dispersion wavelength has moved toward the side of longer wavelength. If the zero-dispersion wavelength moves toward the side of shorter wavelength, the main-signal light and monitoring light can be changed over in similar fashion.

[0201] Fig. 63 shows the flow of processing for controlling changeover of the main-signal light in a case where three waves are used, and Fig. 64 is a diagram useful in describing control for changing over the main-signal light.

[0202] If $I(\lambda_2) = I(\lambda_3)$ holds (step 320 in Fig. 62), the monitoring light of wavelength λ_3 is changed over to main-signal light and the main-signal light of wavelength λ_2 is changed over to monitoring light.

[0203] First, the light attenuators 14_3, 14_1 are closed (step 331; state a in Fig. 64). Next, the center wavelength of the first optical filter 41 is shifted toward the side of longer wavelength and control is performed in such a manner that the wavelengths λ_2, λ_3 fall within the filter range W (step 332, states b, c). In state c, the light attenuator 14_3 is opened gradually and the light attenuator 14_2 is closed gradually (steps 333 - 335; states d - f). If the light attenuator 14_2 is closed fully (state g), the center wavelength of the first optical filter 41 is shifted to λ_3 (step 336; state h). This completes changeover of the main-signal light (step 337). Finally, the light attenuators 14_1, 14_2 are opened and λ_2 is set as the center wavelength of the second optical filter 42 (step 338; state i). Thus, the main-signal light can be changed over while the power of the light is held constant.

(k) Wavelength multiplexing embodiment

(k-1) First embodiment of wavelength multiplexing

[0204] Fig. 65 is a diagram in which a wavelength multiplexing optical transmission system is provided with a wavelength-dispersion compensating function. This system includes a plurality of data transmitters 71a - 71n; a multiplexer 72 for combining light of different wavelengths output by the data transmitters and sending the resulting light to the optical transmission line 30; a demultiplexer 73 for separating light, which has been received from the optical transmission line, according to wavelength; a plurality of receivers 74a - 74n for identifying the data from the light of each of the wavelengths; a dispersion compensation control unit 75 for separately performing dispersion compensation control of each of the multiplexed wavelengths; a dispersion monitoring signal transmitter 76; dispersion monitoring signal receiver 77; and an output wavelength controller 78 which, on the basis of the results of monitoring, controls changeover of main-signal light and monitoring light from each of the transmitters 71a - 71n.

[0205] The transmitters 71a - 71n each have a plurality of light sources LT for generating light of mutually different wavelengths λa_1 - λa_n, λb_1 - λb_n, • • • λn_1 - λn_n; light attenuators ATT for adopting light of prescribed wavelengths λ_A, λ_B, • • • λ_N as main-signal light and light of wavelengths λ_{MA}, λ_{MB}, • • • λ_{MN} as monitoring light, where the light is generated by the plurality of light sources; an arrayed waveguide grating AWG for combining the main-signal light and monitoring light; and an external modulator EMD for modulating light by 40-Gbps data.

[0206] The receivers 74a - 74n respectively include dispersion compensators 91a - 91n which compensate for dispersions $\Delta d1$ - Δdn produced by wavelength differences between a reference wavelength (e.g., the zero-dispersion wavelength) and prescribed light-source wavelengths of the corresponding transmitters 71a - 71n; first optical filters 92a - 92n to which the wavelength of the dispersion-compensated main-signal light is set as the center wavelength; second optical filters 93a - 93n to which the wavelength of the dispersion-compensated monitoring light is set as the center wavelength; first wavelength-dispersion monitors 94a - 94n for detecting and outputting the intensity of a specific frequency component (the intensity of the 40-GHz component) contained in the dispersion-compensated main-signal light; second wavelength-dispersion monitors 95a - 95n for detecting and outputting the intensity of a specific frequency component (the intensity of the 40-GHz component) contained in the dispersion-compensated monitoring light; and 40-Gbps receivers 96a - 96n.

[0207] The dispersion compensation control unit 75 (1) performs dispersion compensation control separately for each of the multiplexed wavelengths and (2), on the basis of the results of control, instructs the output wavelength controller 78 to change over the main-signal light and monitoring light of each transmitter and changes the center wavelengths of the first and second optical filters in each of the receivers. In accordance with the command from the dispersion compensation control unit 75, the output wavelength controller 78 changes over the main-signal light and monitoring light separately on a per-transmitter basis, as shown in Figs. 66A to 66C. It should be noted that dispersion compensation control by the dispersion compensation control unit 75 is carried out in accordance with the method described above in conjunction with Figs. 41 to 51.

[0208] To summarize the foregoing, each of the transmitters 71a - 71n outputs, to the optical transmission line as main-signal light, light having a prescribed wavelength from the light generated by the plurality of light sources and, in order to detect a wavelength for which the transmission characteristic is optimum in regard to the wavelength dispersion of the optical transmission line 30, combines, as monitoring light, light generated from a light source neighboring the light source of the main-signal light with the main-signal light. The receivers 74a - 74n respectively include the dispersion compensators 91a - 91n which compensate for dispersions produced by wavelength differences between the reference wavelength (e.g., the zero-dispersion wavelength) and prescribed light-source wavelengths. The dispersion compensation control unit 75 detects that the ratio between the intensities of the specific frequency component contained in the main-signal light and monitoring light output by the dispersion compensators has attained a predetermined value and instructs the output wavelength controller 78 to changeover the main-signal light and monitoring light. Thus, a wavelength multiplexing optical transmission system can be provided with a dispersion compensation function for every multiplexed wavelength.

[0209] Fig. 65 deals with an example in which control of dispersion compensation for every wavelength is performed using two waves, namely the main-signal light and the monitoring light. However, control of dispersion compensation for every wavelength can also be performed using three waves, namely the main-signal light and two beams of monitoring light. That is, each of the transmitters 71a - 71n outputs, to the optical transmission line as main-signal light, light having a prescribed wavelength from the light generated by the plurality of light sources and, in order to detect a wavelength for which the transmission characteristic is optimum in regard to the wavelength dispersion of the optical transmission line 30, combines, as monitoring light, light generated from two light sources neighboring the light source of the main-signal light with the main-signal light. The receivers 74a - 74n respectively include dispersion compensators which compensate for dispersions produced by wavelength differences between the reference wavelength (e.g., the zero-dispersion wavelength) and prescribed light-source wavelengths. The dispersion compensation control unit 75 compares the intensities of the specific frequency component contained in the main-signal light and two beams of monitoring light output by the dispersion compensators, detects, based upon the results of comparison, a range of wavelengths in which the optimum wavelength is contained, and instructs the output wavelength controller 78 to change over the main-signal light and monitoring light when the intensity ratio of the two wavelengths that bracket the optimum wavelength attains a predetermined value. This arrangement also makes it possible to provide a wavelength multiplexing optical transmission system with a dispersion compensation function for every multiplexed wavelength.

(k-2) Second embodiment of wavelength multiplexing

[0210] Fig. 67 is a diagram of an optical transmission system according to a second embodiment, in which four-wave multiplexed transmission is performed. This system includes one consolidated transmitter 71 and receivers 74a - 74d, provided for respective ones of multiplexed wavelengths, for identifying data from light of the respective wavelengths. The system further includes the demultiplexer 73 for separating light, which has been received from the optical transmission line 30, according to wavelength, one monitor 75 provided for all multiplexed wavelengths, and the dispersion monitoring signal transmitter 76 for transmitting monitoring signal (the result of dispersion monitoring).

[0211] The transmitter has the plurality of light sources 11_1 - 11_n for generating light having different wavelengths λ_1 - λ_n; the light attenuators 14_1 - 14_n for outputting n-number (e.g., four) of light beams as main-signal light (one of which serves as also as monitoring light) from the light generated by the plurality of light sources; a multiplexer/demultiplexer 18 for combining the four main-signal light beams and separating each of the main-signal light beams; external modulators $12b_1$ - $12b_4$ for on/off-modulating main-signal light, which is output by the multiplexer/demultiplexer 18, by 40-Gbps data; and a multiplexer 19 for combining the light output by the external modulators and sending the resulting light to the optical transmission line 30. Further, the transmitter 71 has the dispersion monitoring signal receiver 77, which receives the result of monitoring sent from the dispersion monitoring signal transmitter 76, and the output wavelength controller 78 which, on the basis of the results of monitoring, controls changeover of the four main-signal light beams (monitoring light).

[0212] The receivers 74a - 74d respectively include dispersion compensators $74a_1$ - $74d_1$ which compensate for dispersions conforming to wavelength differences Δd_1 - Δd_4 between the zero-dispersion wavelength and the wavelengths λ_2 - λ_5 of the main-signal light produced by the four light sources; optical filters $74a_2$ - $74d_2$ set to the wavelengths λ_2 - λ_5 of the dispersion-compensated main-signal light as their center frequencies; and 40-Gbps receivers $74a_3$ - $74d_3$.

[0213] The monitor 75, which is for carrying out control of dispersion compensation using, say, light of wavelength λ_5 as main-signal light and light of wavelength λ_4 as monitoring light, has an optical filter 75a, first and second wavelength-dispersion monitors 75b, 75c, and a dispersion compensation control unit 75d. The wavelength λ_4 of the dispersion-compensated monitoring light is set as the center frequency of the optical filter 75a. The first wavelength-dispersion monitor 75b detects and outputs the intensity of the 40-GHz component contained in the dispersion-compensated main-signal light, and the second wavelength-dispersion monitor 75c detects and outputs the intensity of the 40-GHz component contained in the dispersion-compensated monitoring light. The dispersion compensation control unit 75d controls dispersion compensation using the intensity of the 40-GHz component contained in the main-signal light and monitoring light and, based upon the result of control, instructs the output wavelength controller 78 to change over the main-signal light (monitoring light) and changes the center wavelengths of the optical filters $74a_2$ - $74d_2$ in the respective receivers and the center wavelength of the optical filter 75a in the monitor 75. It should be noted that the dispersion compensation control unit 75 controls dispersion compensation in accordance with the method described above in conjunction with Figs. 41 to 51.

[0214] In accordance with the command from the dispersion compensation control unit 75d, the output wavelength controller 78 changes over the main-signal light and monitoring light by shifting all of the four beams of main-signal light one wavelength spacing each toward the side of shorter or longer wavelength, as shown in Fig. 68. This arrangement make it possible to control wavelength dispersion without the addition of a light source exclusively for monitoring.

[0215] It should be noted that dispersion compensation can be controlled using any two adjacent light beams as monitoring light and main-signal light.

(k-3) First modification of second embodiment

[0216] The demultiplexer 63 in Fig. 67 demultiplexes only main-signal light of wavelength λ_5 to the receiver 74d. However, the demultiplexer 73 is capable also of demultiplexing both monitoring light and main-signal light to the receiver 74d. In such case the optical transmission system would be configured as shown in Fig. 69.

(k-4) Second modification of second embodiment

[0217] Fig. 67 deals with a case where dispersion compensation is controlled using two waves, namely main-signal light and monitoring light. However, it is also possible to control wavelength dispersion using three waves, namely main-signal light and two beams of monitoring light. In such case the monitor 75 would use light from three adjacent light sources as the main-signal light and two beams of monitoring light. More specifically, the monitor 75 would detect a range of wavelengths in which the optimum wavelength is contained by comparing the intensities of the specific frequency component contained in the light output from the three adjacent dispersion compensators, and detect the timing of changeover of the main-signal light when the intensity ratio of two wavelengths bracketing the optimum wavelength has attained a set value. In response to the changeover command from the monitor 75, the output wavelength controller 78 would change over the main-signal light in such a manner that the all four beams of the main-signal light would be shifted by one wavelength spacing toward the side of shorter or longer wavelength.

(k-5) Third modification of second embodiment

[0218] According to the second embodiment of wavelength multiplexing, light generated from four adjacent light sources is used as four beams of main-signal light. However, light generated from four light sources that are not adjacent but are staggered or spaced apart by one light source each can be used as the fourth light sources (see Fig. 70, in which the light is output from the shaded light sources). If this arrangement is adopted, it is possible to change over all four of the beams of main-signal light by shifting of four beams of the main-signal light collectively to neighboring unused wavelengths on the side of shorter or longer wavelength, as depicted in Fig. 71. With the third modification, control of changeover is facilitated because the changeover is to wavelengths not being used in signal transmission.

(k-6) Third embodiment of wavelength multiplexing

[0219] Fig. 72 is diagram illustrating an optical transmission system according to a third embodiment in which variable-wavelength light sources are used as transmitter light sources. This system includes the plurality of data transmitters 71a - 71n; the multiplexer 72 for combining light of different wavelengths output by the data transmitters and sending the resulting light to the optical transmission line 30; the demultiplexer 73 for separating light, which has been received from the optical transmission line, according to wavelength; the plurality of receivers 74a - 74n for identifying the data from the light of each of the wavelengths; the dispersion compensation control unit 75 for separately performing dispersion compensation control of each of the multiplexed wavelengths; the dispersion monitoring signal transmitter 76; the dispersion monitoring signal receiver 77; and the output wavelength controller 78 which, on the basis of the results of monitoring, controls the wavelength of the light output from the transmitters 71a - 71n.

[0220] The transmitters 71a - 71n each have a variable-wavelength light source WVL for outputting light of a variable wavelength, and the external modulator EMD for modulating light by 40-Gbps data.

[0221] The receivers 74a - 74n respectively include the dispersion compensators 91a - 91n which compensate for dispersions Δd1 - Δdn produced by wavelength differences $\Delta\lambda_1$ - $\Delta\lambda_n$ between a reference wavelength (e.g., the zero-dispersion wavelength) and wavelengths λ_A - λ_N of light output from the variable-wavelength light sources WVL of the corresponding transmitters 71a - 71n; the optical filters 92a - 92n to which the wavelengths λ_A -λ_N of the dispersion-compensated light are set as the center wavelengths; the wavelength-dispersion monitors 94a - 94n for detecting and outputting the intensity of a specific frequency component (the intensity of the 40-GHz component) contained in the dispersion-compensated light; and the 40-Gbps receivers 96a - 96n. The wavelength-dispersion monitors 94a - 94n are each constituted by a photodiode (PD), bandpass filter (BPF), amplifier and power meter.

[0222] The dispersion compensation control unit 75 (1) performs dispersion compensation control separately for each of the multiplexed wavelengths λ_A - λ_N and (2), on the basis of the results of control, instructs the output wavelength controller 78 of the wavelengths of light output from the transmitters 71a - 71n and changes the center wavelengths of the optical filters 92a - 92n in each of the receivers. By way of example, the dispersion compensation control unit 75 changes the wavelength of light from the variable-wavelength light sources WVL separately on a per-transmitter basis via the output wavelength controller 78, detects the optimum wavelength for which the intensity of a specific frequency component, which is contained in the baseband spectrum signal of the received light, indicates the minimum value, and instructs the output wavelength controller 78 to change over wavelength in such a manner that light of the optimum wavelength will be output. In response to being so instructed by the dispersion compensation control unit 75, the output wavelength controller 78 controls the wavelength of the light from the variable-wavelength light sources WVL individually on a per-transmitter basis.

[0223] The foregoing is for a case where the receivers 74a - 74n are respectively provided with the wavelength-dispersion monitors 94a - 94n, and the dispersion compensation control unit 75 controls the wavelengths of the transmitters 71a - 71n individually. However, an arrangement can be adopted in which a wavelength-dispersion monitor is provided in only one receiver and controls the wavelengths of all of the transmitters 71a - 71n. Fig. 73 is a diagram of an optical transmission system representing such a modification. Here only the receiver 74n is provided with a wavelength-dispersion monitor, which is monitor 94n.

[0224] The dispersion compensation control unit 75 changes the wavelength of light from the variable-wavelength light source WVL of transmitter 71n via the output wavelength controller 78, detects the optimum wavelength for which the intensity of a specific frequency component, which is contained in the baseband spectrum signal of the received light, indicates the minimum value, calculates the difference $\Delta\lambda$ between this and the optimum wavelength thus far, and instructs the output wavelength controller 78 to change the wavelength of light, which is output from each of transmitters 71a - 71n, by an amount equivalent to $\Delta\lambda$. In response to being so instructed by the dispersion compensation control unit 75, the output wavelength controller 78 performs control so as to change, by $\Delta\lambda$, the wavelength of the light from the variable-wavelength light sources WVL of the respective transmitters.

[0225] Thus, in accordance with the present invention, it is possible to compensate for wavelength dispersion by outputting, to an optical transmission line which exhibits wavelength dispersion, light having a wavelength for which the transmission characteristic is optimum for this wavelength dispersion, this being accomplished without using a tunable laser.

[0226] In accordance with the present invention, it is possible to arrange it so that neither signal interruption nor signal degradation occurs at the time of wavelength switching even if a plurality of light sources having different wavelengths are used, as when use is made of a semiconductor array laser or a plurality of discrete semiconductor lasers.

[0227] In accordance with the present invention, it is possible to compensate for wavelength dispersion by using an arrayed waveguide grating (AWG), a star coupler, a variable-wavelength filter or a light attenuator to change, in a simple manner, the wavelength of light output to an optical transmission line.

[0228] In accordance with the present invention, it is possible to so arrange it that dispersion compensation can be carried out accurately by detecting zero-dispersion wavelength even in a case where a plurality of light sources having different wavelengths are used.

[0229] In accordance with the present invention, the light source of light output to an optical transmission line is changed over when zero-dispersion wavelength takes on a value intermediate the wavelengths of neighboring light sources, in a case where a plurality of light sources of different wavelengths are used. As a result, it is possible to eliminate or reduce signal delay before and after wavelength changeover and to prevent signal degradation.

[0230] In accordance with the present invention, the wavelength of output light is minutely changed, thereby obtaining zero-dispersion wavelength and making it possible to compensate for wavelength dispersion caused by aging.

[0231] In accordance with the present invention, monitoring light is multiplexed with main-signal light, whereby it is possible to readily detect whether zero-dispersion wavelength has shifted in the direction of long wavelength or short wavelength and whether zero-dispersion wavelength has become an intermediate wavelength between wavelengths of neighboring light sources.

[0232] In accordance with the present invention, the wavelength of monitoring light is made sufficiently distant from the wavelength of main-signal light. As a result, four-wave mixing can be prevented from occurring.

[0233] In accordance with the present invention, the polarizations of main-signal light and monitoring light are made orthogonal in a case where the monitoring light is multiplexed with the main-signal light and then transmitted. As a result, it is possible to improve detection precision of, e.g., the direction of fluctuation of zero-dispersion wavelength.

[0234] In accordance with the present invention, dispersion compensation is controlled using three waves, namely main-signal light and two beams of monitoring light. As a result, it is unnecessary to constantly monitor an increase or decrease in the intensity of a specific component of each wavelength; it will suffice merely to compare the absolute values of the intensities of specific components of three waves at a certain time. This facilitates control of dispersion compensation.

[0235] In accordance with the present invention, regardless of the fact that the characteristic of the intensity of the specific frequency component differs depending upon whether the optical modulation scheme is NRZ modulation, OTDM modulation or RZ modulation, wavelength dispersion can be controlled in the case of NRZ modulation by detecting the minimum at the foot of the peak of the characteristic of the intensity of the specific frequency component, in the case of OTDM modulation by detecting the valley between two peaks and in the case of RZ modulation by detecting a maximum value.

[0236] In accordance with the present invention, dispersion compensation can be controlled at the time of wavelength multiplexing transmission.

[0237] As many apparently widely different embodiments of the present invention can be made without departing from the spirit and scope thereof, it is to be understood that the invention is not limited to the specific embodiments thereof except as defined in the appended claims.

Claims

1. An optical transmitter having a wavelength dispersion compensating function, comprising:

    a plurality of light sources for outputting light having wavelengths that differ from one another; and
    optical output means for outputting, to an optical transmission line, light of a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line, the output light being obtained from light output by said plurality of light sources.

2. The optical transmitter according to claim 1, wherein a semiconductor array laser is used as said plurality of light sources.

3. The optical transmitter according to claim 1, wherein a plurality of discrete semiconductor lasers are used as said plurality of light sources.

4. The optical transmitter according to claim 1, wherein said optical output means outputs to the optical transmission line light having a wavelength nearest to zero-dispersion wavelength for which the wavelength dispersion value of the optical transmission line becomes zero, the output light being obtained from light output by said plurality of light sources.

5. An optical transmitter having a wavelength dispersion compensating function, comprising:

    a plurality of light sources for outputting light having wavelengths that differ from one another;
    optical output means for outputting, to an optical transmission line, light of a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line, the output light being obtained from light output by said plurality of light sources; and
    wavelength varying means for changing over the light generated by said light sources and outputting this light to the optical transmission line, thereby changing the wavelength of light output to the optical transmission line;
    wherein the wavelength of light output to the optical transmission line is changed, before start of operation of an optical transmission system, in order to detect a wavelength whose transmission characteristic is optimum with regard to the wavelength dispersion exhibited by this optical transmission line, and the light having the detected optimum wavelength is output to the optical transmission line during system operation.

6. The optical transmitter according to claim 5, further comprising wavelength detection means for detecting the wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line;

    wherein light having the optimum wavelength detected by said wavelength detection means is output to the optical transmission line.

7. The optical transmitter according to claim 6, wherein said wavelength detection means detects the optimum wavelength based upon intensity of a specific frequency component contained in a received baseband spectrum signal.

8. The optical transmitter according to claim 7, wherein the specific frequency is a data bit-rate frequency.

9. The optical transmitter according to claim 5, further comprising light attenuators disposed on an output side of respective ones of said light sources;

    wherein said wavelength varying means changes the wavelength of light output to the optical transmission line by controlling amount of light attenuation of each of said light attenuators.

10. The optical transmitter according to claim 5, wherein said optical output means includes:

multiplexing means for multiplexing light generated by each of said light sources; and
a variable-wavelength filter for selecting and outputting a desired wavelength;
wherein said wavelength varying means changes the wavelength of light output to the optical transmission line by controlling said variable-wavelength filter.

11. The optical transmitter according to claim 5, wherein the optimum wavelength is zero-dispersion wavelength of the optical transmission line, and, during system operation, said optical output means outputs to the optical transmission line light having a wavelength nearest to the zero-dispersion wavelength, the output light being obtained from light output by said plurality of light sources.

12. An optical transmitter having a wavelength dispersion compensating function, comprising:

a plurality of light sources for outputting light having wavelengths that differ from one another;
optical output means for changing wavelength of light, which is output to an optical transmission line, by changing over light generated by said plurality of light sources, and selecting and outputting light of a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line; and
a modulator for modulating the light, which is output from said optical output means, by transmitted data, and sending the modulated light to the optical transmission line;
said modulator modulating the light in such a manner that intensity of a specific frequency component contained in a received baseband spectrum signal on the receiving side indicates an extreme value at zero-dispersion wavelength; and
said optical output means changes the wavelength of light output to the optical transmission line in order to detect the zero-dispersion wavelength or a wavelength of a light source closest to the zero-dispersion wavelength before start of operation of an optical transmission system, and outputs light having the zero-dispersion wavelength or the wavelength closest to the zero-dispersion wavelength as main-signal light during system operation.

13. The optical transmitter according to claim 12, wherein when light of the zero-dispersion wavelength is modulated, said modulator modulates the light in such a manner that the intensity of the specific frequency component contained in a received baseband spectrum signal on the receiving side becomes a minimum value.

14. The optical transmitter according to claim 12, wherein when light of the zero-dispersion wavelength is modulated, said modulator modulates the light in such a manner that the intensity of the specific frequency component contained in a received baseband spectrum signal on the receiving side becomes a maximum value.

15. An optical transmitter having a wavelength dispersion compensating function, comprising:

a plurality of light sources for outputting light having wavelengths that differ from one another;
optical output means for outputting, to an optical transmission line, light of a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line, the output light being obtained from light output by said plurality of light sources; and
first wavelength varying means for varying the wavelength of the light output to the optical transmission line in order to detect a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line;
wherein the light having the optimum wavelength detected during operation of the optical transmission system is output to the optical transmission line.

16. The optical transmitter according to claim 15, further comprising second wavelength varying means for changing over the light generated by said light sources and outputting this light to the optical transmission line, thereby changing the wavelength of light output to the optical transmission line;
wherein the wavelength of light output to the optical transmission line is changed by the second wavelength varying means, before start of operation of an optical transmission system, in order to decide a wavelength whose transmission characteristic is optimum with regard to the wavelength dispersion exhibited by the optical transmission line, and the light having the optimum wavelength is output to the optical transmission line and the wavelength of the light is varied by the first wavelength varying means during system operation.

17. The optical transmitter according to claim 15, further comprising wavelength detection means for detecting the

wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line;

wherein light having the optimum wavelength detected by said wavelength detection means is output to the optical transmission line.

18. The optical transmitter according to claim 17, wherein said wavelength detection means detects the optimum wavelength based upon intensity of a specific frequency component contained in a received baseband spectrum signal.

19. The optical transmitter according to claim 15, wherein the optimum wavelength is zero-dispersion wavelength of the optical transmission line, and said optical output means outputs to the optical transmission line light having a wavelength nearest to the zero-dispersion wavelength, the output light being obtained from light output by said plurality of light sources.

20. The optical transmitter according to claim 19, further comprising light-source changeover means which, when the zero-dispersion wavelength has shifted to a wavelength intermediate the wavelength of a light source that generates light output to the optical transmission line and the wavelength of a light source neighboring this light source, is for changing over the light output to the optical transmission line from a present light source to the neighboring light source without instantaneous interruption of light.

21. The optical transmitter according to claim 20, wherein light output to the optical transmission line is changed over without instantaneous interruption by gradually reducing amount of current injected into the present light source and gradually increasing amount of current injected into the neighboring light source.

22. The optical transmitter according to claim 20, wherein when light output to the optical transmission line is changed over from the present light source to the neighboring light source, light from the present light source and light from the neighboring light source is output to the optical transmission line simultaneously and then the output of light to the optical transmission line from the present light source is halted.

23. The optical transmitter according to claim 16, further comprising light attenuators disposed on an output side of respective ones of said light sources;

wherein said second wavelength varying means changes the wavelength of light output to the optical transmission line by controlling amount of light attenuation of each of said light attenuators.

24. The optical transmitter according to claim 16, wherein said optical output means includes:

multiplexing means for multiplexing light generated by each of said light sources; and
a variable-wavelength filter for selecting and outputting a desired wavelength;
wherein said second wavelength varying means changes the wavelength of light output to the optical transmission line by controlling said variable-wavelength filter.

25. An optical transmitter having a wavelength dispersion compensating function, comprising:

a plurality of light sources for outputting light having wavelengths that differ from one another;
optical output means for outputting, as main-signal light to an optical transmission line, light of a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line, the output light being obtained from light output by said plurality of light sources; and
multiplexing means for multiplexing, with the main-signal light, monitoring light for detecting a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line;
wherein the monitoring light is multiplexed with the main-signal light during operation of an optical transmission system and the light having the detected optimum wavelength is output to the optical transmission line as the main-signal light.

26. The optical transmitter according to claim 25, further comprising wavelength varying means for changing over the light generated by said light sources and outputting this light to the optical transmission line, thereby changing the wavelength of light output to the optical transmission line;

wherein the wavelength of light output to the optical transmission line is changed by the wavelength varying means, before start of operation of an optical transmission system, in order to decide a wavelength whose transmission characteristic is optimum with regard to the wavelength dispersion exhibited by the optical transmission line, and the light having the optimum wavelength is output as main-signal light to the optical transmission line during system operation.

27. The optical transmitter according to claim 25, wherein said optical output means outputs, as main-signal light to the optical transmission line, light having a wavelength nearest to the zero-dispersion wavelength, the output light being obtained from light output by said plurality of light sources.

28. The optical transmitter according to claim 27, further comprising light-source changeover means which, when the zero-dispersion wavelength has shifted to a wavelength intermediate the wavelength of a light source that generates main-signal light output to the optical transmission line and a light source that generates monitoring light neighboring this light source, is for changing over the main-signal light from a present light source to the neighboring light source without instantaneous interruption of light.

29. The optical transmitter according to claim 28, wherein light output to the optical transmission line is changed over without instantaneous interruption by gradually reducing amount of current injected into the present light source and gradually increasing amount of current injected into the neighboring light source.

30. The optical transmitter according to claim 28, wherein when light output to the optical transmission line is changed over from the present light source to the neighboring light source, light from the present light source and light from the neighboring light source is output to the optical transmission line simultaneously and then the output of light to the optical transmission line from the present light source is halted.

31. The optical transmitter according to claim 26, further comprising light attenuators disposed on an output side of respective ones of said light sources;

wherein said wavelength varying means changes the wavelength of light output to the optical transmission line by controlling amount of light attenuation of each of said light attenuators.

32. The optical transmitter according to claim 26, wherein said optical output means includes:

multiplexing means for multiplexing light generated by each of said light sources; and
a variable-wavelength filter for selecting and outputting a desired wavelength;
wherein said wavelength varying means changes the wavelength of light output to the optical transmission line by controlling said variable-wavelength filter.

33. The optical transmitter according to claim 25, further comprising:

means for making polarization of signal light and polarization of monitoring light orthogonal; and
means for maintaining the polarizations of the signal light and monitoring light.

34. The optical transmitter according to claim 25, wherein the monitoring light is light generated by a light source neighboring, in terms of wavelength, a light source that generates main-signal light.

35. The optical transmitter according to claim 25, wherein the monitoring light is light generated by a light source which is sufficiently remote, in terms of wavelength, from a light source that generates main-signal light.

36. The optical transmitter according to claim 25, wherein the monitoring light is light generated by a light source exclusively for monitoring of wavelength dispersion.

37. The optical transmitter according to claim 25, further comprising wavelength detection means for detecting the wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line;

wherein light having the optimum wavelength detected by said wavelength detection means is output to the optical transmission line.

38. The optical transmitter according to claim 37, wherein said wavelength detection means detects the optimum wavelength based upon intensity of a specific frequency component contained in a received baseband spectrum signal.

39. An optical transmission system having a wavelength dispersion compensating function, comprising:

a plurality of light sources for generating light having wavelengths that differ from one another;
optical output means for outputting, to an optical transmission line, prescribed light obtained from light generated by said plurality of light sources;
wavelength varying means for changing over the light generated by said light sources and outputting this light to the optical transmission line, thereby changing the wavelength of light output to the optical transmission line; and
wavelength detection means for detecting the wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line;
wherein the wavelength of light output to the optical transmission line is changed by the wavelength varying means and a wavelength whose transmission characteristic is optimum with regard to the wavelength dispersion exhibited by this optical transmission line is detected before start of operation of the optical transmission system, and the light having the detected optimum wavelength is output to the optical transmission line during system operation.

40. The system according to claim 39, wherein the optimum wavelength is zero-dispersion wavelength, and said optical output means outputs to the optical transmission line light having a wavelength nearest to the zero-dispersion wavelength, the output light being obtained from light output by said plurality of light sources.

41. An optical transmission system having a wavelength dispersion compensating function, comprising:

a plurality of light sources for generating light having wavelengths that differ from one another;
optical output means for outputting, to an optical transmission line, prescribed light obtained from light generated by said plurality of light sources;
wavelength varying means for controlling said optical output means to change over the light generated by said light sources, thereby changing the wavelength of light output to the optical transmission line; and
optimum-wavelength detecting means for detecting a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line, based upon intensity of a specific frequency component contained in a baseband spectrum signal of received light;
wherein before start of operation of the optical transmission system, said wavelength varying means changes the wavelength of light output to the optical transmission line by controlling changeover of light generated by said light sources, and said optimum-wavelength detecting means detects, as optimum wavelength, a wavelength for which the intensity of the specific frequency component contained in the baseband spectrum signal of received light is minimum; and
during system operation, the light of the detected optimum wavelength is output to the optical transmission line.

42. An optical transmission system having a wavelength dispersion compensating function, comprising:

a plurality of light sources for generating light having wavelengths that differ from one another;
optical output means for outputting, to an optical transmission line, prescribed light obtained from among light generated by said plurality of light sources;
wavelength varying means for controlling said optical output means to change over the light generated by said light sources, thereby changing the wavelength of light output to the optical transmission line;
optimum-wavelength detecting means for detecting a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line, based upon intensity of a specific frequency component contained in a baseband spectrum signal of received light; and
dispersion add-on means, which is provided in front of said optimum-wavelength detecting means, for furnishing received light with dispersion conforming to a wavelength difference between a wavelength for which the intensity of the specific frequency component is maximized and a wavelength for which the intensity of the specific frequency component is minimized;
wherein before start of operation of the optical transmission system, said wavelength varying means changes the wavelength of light output to the optical transmission line by changing over light generated by said light sources, and said optimum-wavelength detecting means detects a wavelength λ_m for which the intensity of the specific frequency component contained in the baseband spectrum signal of received light, which enters via said dispersion add-on means, is maximum; and
during system operation, light is output to the optical transmission line so that the wavelength of light that enters said optimum-wavelength detecting means via said dispersion add-on means becomes λm.

43. The system according to claim 42, wherein a bit-rate frequency signal necessary for receiving data is generated from an output side of said dispersion add-on means.

44. An optical transmission system having a wavelength dispersion compensating function, comprising:

a plurality of light sources for generating light having wavelengths that differ from one another;
optical output means for outputting, to an optical transmission line, prescribed light obtained from among light generated by said plurality of light sources;
wavelength varying means for controlling said optical output means to change over the light generated by said light sources, thereby changing the wavelength of light output to the optical transmission line; and
optimum-wavelength detecting means for detecting a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line, based upon intensity of a specific frequency component contained in a baseband spectrum signal of received light;
wherein before start of operation of the optical transmission system, said wavelength varying means changes the wavelength of light output to the optical transmission line by changing over light generated by said light sources, and said optimum-wavelength detecting means detects, as optimum wavelength, a wavelength for which the intensity of the specific frequency component contained in the baseband spectrum signal of received light is maximum; and
during system operation, the light of the detected optimum wavelength is output to the optical transmission line.

45. An optical transmission system having a wavelength dispersion compensating function, comprising:

a plurality of light sources for generating light having wavelengths that differ from one another;
optical output means for outputting, to an optical transmission line, prescribed light obtained from among light generated by said plurality of light sources;
wavelength varying means for controlling said optical output means to change over the light generated by said light sources, thereby changing the wavelength of light output to the optical transmission line;
optimum-wavelength detecting means for detecting a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line, based upon intensity of a specific frequency component contained in a baseband spectrum signal of received light; and
dispersion add-on means, which is provided in front of said optimum-wavelength detecting means, for furnishing received light with dispersion conforming to a wavelength difference between a wavelength for which the intensity of the specific frequency component is maximized and a wavelength for which the intensity of the specific frequency component is minimized;
wherein before start of operation of the optical transmission system, said wavelength varying means changes the wavelength of light output to the optical transmission line by changing over light generated by said light sources, and said optimum-wavelength detecting means detects a wavelength λ_{min} for which the intensity of the specific frequency component contained in the baseband spectrum signal of received light, which enters via said dispersion add-on means, is minimum; and
during system operation, light is output to the optical transmission line so that the wavelength of light that enters said optimum-wavelength detecting means via said dispersion add-on means becomes λm.

46. An optical transmission system having a wavelength dispersion compensating function, comprising:

a plurality of light sources for generating light having wavelengths that differ from one another;
optical output means for outputting, to an optical transmission line, prescribed light obtained from among light generated by said plurality of light sources;
first wavelength varying means for changing over the light generated by said light sources and outputting this light to the optical transmission line, thereby changing the wavelength of light output to the optical transmission line;
second wavelength varying means for varying the wavelength of the light output to the optical transmission line in order to detect a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by this optical transmission line; and
wavelength detection means for detecting the wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line;
wherein, before start of operation of the system, light generated by the light sources is changed over to change the wavelength of light output to the optical transmission line, and wavelength for which the transmission characteristic is optimum is detected; and

during system operation, the light having the detected optimum wavelength is output to the optical transmission line, the wavelength of this light is varied by the second wavelength varying means to detect variation of the optimum wavelength, and the light having the detected optimum wavelength is output to the optical transmission line.

47. The system according to claim 46, wherein the optimum wavelength is zero-dispersion wavelength, and said optical output means outputs to the optical transmission line light having a wavelength nearest to the zero-dispersion wavelength, the output light being obtained from light output by said plurality of light sources.

48. An optical transmission system having a wavelength dispersion compensating function, comprising:

a plurality of light sources for generating light having wavelengths that differ from one another;
optical output means for outputting, as main-signal light to an optical transmission line, prescribed light obtained from among light generated by said plurality of light sources;
wavelength varying means for changing over the light generated by said light sources and outputting this light to the optical transmission line, thereby changing the wavelength of light output to the optical transmission line; and
multiplexing means for multiplexing, with the main-signal light, monitoring light for detecting a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line; and
wavelength detection means for detecting a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line;
wherein, before start of operation of the system, light generated by the light sources is changed over to change the wavelength of light output to the optical transmission line, and wavelength for which the transmission characteristic is optimum is detected;
when the system is operating, the light having the detected optimum wavelength is output as main-signal light to the optical transmission line and monitoring light is multiplexed with this main-signal light; and
optimum wavelength during system operation is detected, the light having this optimum wavelength is output as new main-signal light to the optical transmission line, and monitoring light is multiplexed with this main-signal light.

49. The system according to claim 48, wherein the optimum wavelength is zero-dispersion wavelength, and said optical output means outputs to the optical transmission line light having a wavelength nearest to the zero-dispersion wavelength, the output light being obtained from light output by said plurality of light sources.

50. The system according to claim 49, wherein said wavelength detection means detects the optimum wavelength based upon intensity of a specific frequency component contained in a received baseband spectrum signal before start of operation of the system.

51. The system according to claim 49, wherein, during operation of the system, said wavelength detection means detects (1) direction in which the zero-dispersion wavelength fluctuates and (2) the fact that the zero-dispersion wavelength has shifted to a wavelength intermediate wavelength of the light source of the main-signal light and wavelength of the neighboring light source, these being detected from intensity of a specific frequency component in a baseband spectrum signal of the received main-signal light and intensity of a specific frequency component in a baseband spectrum signal of monitoring light.

52. The system according to claim 51, further comprising means for changing over the main-signal light from a present light source to a neighboring light source without instantaneous interruption of light when the zero-dispersion wavelength has shifted to a wavelength intermediate the wavelength of the present light source and the wavelength of the neighboring light source.

53. An optical transmission system having a wavelength dispersion compensating function, comprising:

a plurality of light sources for generating light having wavelengths that differ from one another;
optical output means for outputting, as main-signal light to an optical transmission line, light having a prescribed wavelength, the output light being obtained from light generated by said plurality of light sources;
wavelength varying means for changing over the light generated by said light sources and outputting this light to the optical transmission line, thereby changing the wavelength of light output to the optical transmission line;

multiplexing means for selecting, as monitoring light, light generated by a prescribed light source and multiplexing the monitoring light with the main-signal light in order to detect a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line; and

wavelength-changeover detecting means for detecting timing of changeover of the main-signal light at such time that a ratio between intensities of a specific frequency component contained in the main-signal light and in the monitoring light has attained a predetermined value.

54. The system according to claim 53, wherein when main-signal light is changed over, monitoring light is changed over to main-signal light and main-signal light is changed over to monitoring light.

55. The system according to claim 54, wherein said wavelength-changeover detecting means detects direction of fluctuation of zero-dispersion wavelength and a wavelength range in which zero-dispersion wavelength is contained based upon intensities of a specific frequency component contained in each of main-signal light and monitoring light, and detects timing of changeover of the monitoring light at such time that zero-dispersion wavelength departs from a range of wavelengths λ_m to λ_s, where λ_m to λ_s represent wavelengths of the main-signal light and monitoring light, respectively.

56. An optical transmission system having a wavelength dispersion compensating function, comprising:

a plurality of light sources for generating light having wavelengths that differ from one another;
optical output means for outputting, as main-signal light to an optical transmission line, light having a prescribed wavelength, the output light being obtained from light generated by said plurality of light sources;
wavelength varying means for changing over the light generated by said light sources and outputting this light to the optical transmission line, thereby changing the wavelength of light output to the optical transmission line;
multiplexing means for selecting, as monitoring light, light beams generated by two light sources and multiplexing the monitoring light with the main-signal light in order to detect a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line; and
wavelength-changeover detecting means for detecting a wavelength range in which optimum wavelength is included by comparing intensities of a specific frequency component contained in the main-signal light and in the two light beams of monitoring light, and detecting timing of changeover of the main-signal light at such time that an intensity ratio of two wavelengths between which the optimum wavelength is sandwiched has attained a predetermined value.

57. The system according to claim 56, wherein when main-signal light is changed over, monitoring light is changed over to main-signal light and main-signal light is changed over to monitoring light.

58. The system according to claim 57, wherein said wavelength-changeover detecting means detects a wavelength range in which zero-dispersion wavelength is contained based upon intensities of a specific frequency component contained in the main-signal light and in the two beams of monitoring light, and detects timing of changeover of the monitoring light at such time that zero-dispersion wavelength has become shorter than or longer than all the wavelengths of the main-signal light and of the two beams of monitoring light.

59. A wavelength multiplexing optical transmission system having a plurality of data transmitters, a multiplexer for multiplexing light of different wavelengths output by these data transmitters and sending the resulting light to an optical transmission line, a demultiplexer for separating light, which has been received from the optical transmission line, according to wavelength, and a plurality of receivers for identifying the data from the light of each of the wavelengths, said system being provided with a wavelength-dispersion compensating function which compensates for wavelength dispersion exhibited by the optical transmission line, wherein:

each data transmitter includes:
a plurality of light sources for generating light having wavelengths that differ from one another;
optical output means for outputting, as main-signal light to an optical transmission line, light having a prescribed wavelength, the output light being obtained from light generated by said plurality of light sources;
wavelength varying means for changing over the light generated by said light sources and outputting this light to the optical transmission line, thereby changing the wavelength of light output to the optical transmission line;
multiplexing means for selecting, as monitoring light, light generated by a prescribed light source and multiplexing the monitoring light with the main-signal light in order to detect a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line; and

an optical modulator for modulating the multiplexed light by transmitted data and outputting the modulated light; and

each receiver includes:

a dispersion compensator for compensating for a dispersion produced by a wavelength difference between zero-dispersion wavelength and a wavelength of light generated by a prescribed light source of the transmitter that corresponds to the receiver;

detecting means for detecting timing of changeover of the main-signal light at such time that a ratio between intensities of a specific frequency component contained in the dispersion-compensated main-signal light and in the dispersion-compensated monitoring light has attained a predetermined value.

60. A wavelength multiplexing optical transmission system having a wavelength-dispersion compensating function which compensates for wavelength dispersion exhibited by an optical transmission line, comprising:

a plurality of transmitters for modulating light by transmitted data and transmitting the modulated light;

an output wavelength controller for controlling the wavelength of light output from each transmitter;

a multiplexer for multiplexing light of different wavelengths output by respective ones of said transmitters and sending the resulting light to the optical transmission line;

a demultiplexer for separating light, which has been received from the optical transmission line, according to wavelength;

a plurality of receivers for identifying the transmitted data from optical signals of the respective wavelengths; and

a dispersion monitor for transmitting, to said output wavelength controller, a wavelength control signal which controls the wavelength of light output from each transmitter based upon intensity of a specific frequency component contained in each received optical signal of each wavelength, or a wavelength control signal which controls the wavelengths of the light output from all transmitters based upon intensity of a specific frequency component contained in a received optical signal of one prescribed wavelength; wherein

each of said transmitters includes:

a variable-wavelength light source for outputting light of a wavelength different from the wavelengths of light output by other variable-wavelength light sources; and

an optical modulator for modulating the light from said variable-wavelength light source by the transmitted data and inputting the modulated light to said multiplexer; and

each of said receivers includes:

a dispersion compensator for compensating for dispersion produced by a wavelength difference between zero-dispersion wavelength and the wavelength of light output from the transmitter that corresponds to this receiver; and

a data receiver for identifying the transmitted data from an optical signal output by said dispersion compensator;

at least one of said receivers further including a detector for detecting intensity of a specific frequency component contained in the optical signal output by said dispersion compensator and inputting the detected intensity to said dispersion monitor;

said dispersion monitor transmitting, to said output wavelength controller, a signal which controls the wavelength of a corresponding transmitter or the wavelengths of all transmitters based upon the intensity of a specific frequency component detected by said detector of the receiver; and

said output wavelength controller individually controlling the wavelength of the variable-wavelength light source of each transmitter based upon the wavelength control signal received from said dispersion monitor.

61. A wavelength multiplexing optical transmission system having a plurality of data transmitters, a multiplexer for multiplexing light of different wavelengths output by these data transmitters and sending the resulting light to an optical transmission line, a demultiplexer for separating light, which has been received from the optical transmission line, according to wavelength, and a plurality of receivers for identifying transmitted data from the received light of each of the wavelengths, said system being provided with a wavelength-dispersion compensating function which compensates for wavelength dispersion exhibited by the optical transmission line, wherein:

each data transmitter includes:

a plurality of light sources for generating light having wavelengths that differ from one another;

optical output means for outputting, as main-signal light to an optical transmission line, light having a prescribed wavelength, the output light being obtained from light generated by said plurality of light sources;

wavelength varying means for changing over the light generated by said light sources and outputting this light

to the optical transmission line, thereby changing the wavelength of the main-signal light output to the optical transmission line;
multiplexing means for selecting, as monitoring light, light beams generated by two light sources and multiplexing the monitoring light with the main-signal light in order to detect a wavelength whose transmission characteristic is optimum with regard to wavelength dispersion exhibited by the optical transmission line; and
an optical modulator for modulating the multiplexed light by the transmitted data and outputting the modulated light; and
each receiver includes:
a dispersion compensator for compensating for a dispersion produced by a wavelength difference between zero-dispersion wavelength and a wavelength of light generated by a prescribed light source of the transmitter that corresponds to the receiver; and
detecting means for detecting a wavelength range in which optimum wavelength is included by comparing intensities of a specific frequency component contained in the dispersion-compensated main-signal light and in the two dispersion-compensated light beams of monitoring light, and detecting timing of changeover of the main-signal light at such time that an intensity ratio of two wavelengths between which the optimum wavelength is sandwiched has attained a predetermined value.

62. A wavelength multiplexing optical transmission system having a transmitter, an optical transmission line and receivers, said system being provided with a wavelength-dispersion compensating function which compensates for wavelength dispersion exhibited by the optical transmission line, said system comprising:

a plurality of light sources for generating light having wavelengths that differ from one another;
means for selecting, as main-signal light, n-number of beams of light from light generated by said plurality of light sources;
optical modulators for modulating each of the selected beams of main-signal light by n-number of items of transmitted data and outputting the modulated light;
a multiplexer for multiplexing the light output from said optical modulators and sending the multiplexed light to the optical transmission line;
a demultiplexer for separating light, which has been received from the optical transmission line, according to wavelength;
n-number of dispersion compensators for compensating for dispersion produced by wavelength differences between zero-dispersion wavelength and each wavelength of light generated by said n-number of light sources;
receivers for identifying the transmitted data from optical signals output by each of said dispersion compensators; and
detecting means for detecting timing of changeover of the n-number of beams of main-signal light at such time that a ratio between intensities of a specific frequency component contained in light output from two adjacent dispersion compensators has attained a predetermined value;
wherein when the main-signal light is changed over, said means for selecting the main-signal light changes over the main-signal light in such a manner that all n-number of the beams of main-signal light are shifted one wavelength spacing toward the side of shorter or longer wavelength.

63. The system according to claim 62, wherein said means for selecting the main-signal light selects n-number of beams of light of every other wavelength as main-signal light and, when the main-signal light is changed over, changes over the main-signal light in such a manner that all n-number of the beams of main-signal light are shifted collectively to neighboring unused wavelengths on the side of shorter or longer wavelength.

64. A wavelength multiplexing optical transmission system having a transmitter, an optical transmission line and receivers, said system being provided with a wavelength-dispersion compensating function which compensates for wavelength dispersion exhibited by the optical transmission line, said system comprising:

a plurality of light sources for generating light having wavelengths that differ from one another;
means for selecting, as main-signal light, n-number ($n \geq 3$) of beams of light from light generated by said plurality of light sources;
optical modulators for modulating each of the selected beams of main-signal light by n-number of items of transmitted data and outputting the modulated light;
a multiplexer for multiplexing the light output from said optical modulators and sending the multiplexed light to the optical transmission line;

a demultiplexer for separating light, which has been received from the optical transmission line, according to wavelength;

n-number of dispersion compensators for compensating for dispersion produced by wavelength differences between zero-dispersion wavelength and each wavelength of light generated by said n-number of light sources;

receivers for identifying data from optical signals output by each of said dispersion compensators; and

detecting means for detecting a wavelength range in which optimum wavelength is included by comparing intensities of a specific frequency component contained in light output from three adjacent dispersion compensators, and detecting timing of changeover of the main-signal light at such time that an intensity ratio of two wavelengths between which the optimum wavelength is sandwiched has attained a predetermined value;

wherein when the main-signal light is changed over, said means for selecting the main-signal light changes over the main-signal light in such a manner that all n-number of the beams of main-signal light are shifted one wavelength spacing toward the side of shorter or longer wavelength.

65. The system according to claim 64, wherein said means for selecting the main-signal light selects n-number of beams of light of every other wavelength as main-signal light and, when the main-signal light is changed over, changes over the main-signal light in such a manner that all n-number of the beams of main-signal light are shifted collectively to neighboring unused wavelengths on the side of shorter or longer wavelength.

FIG. 1

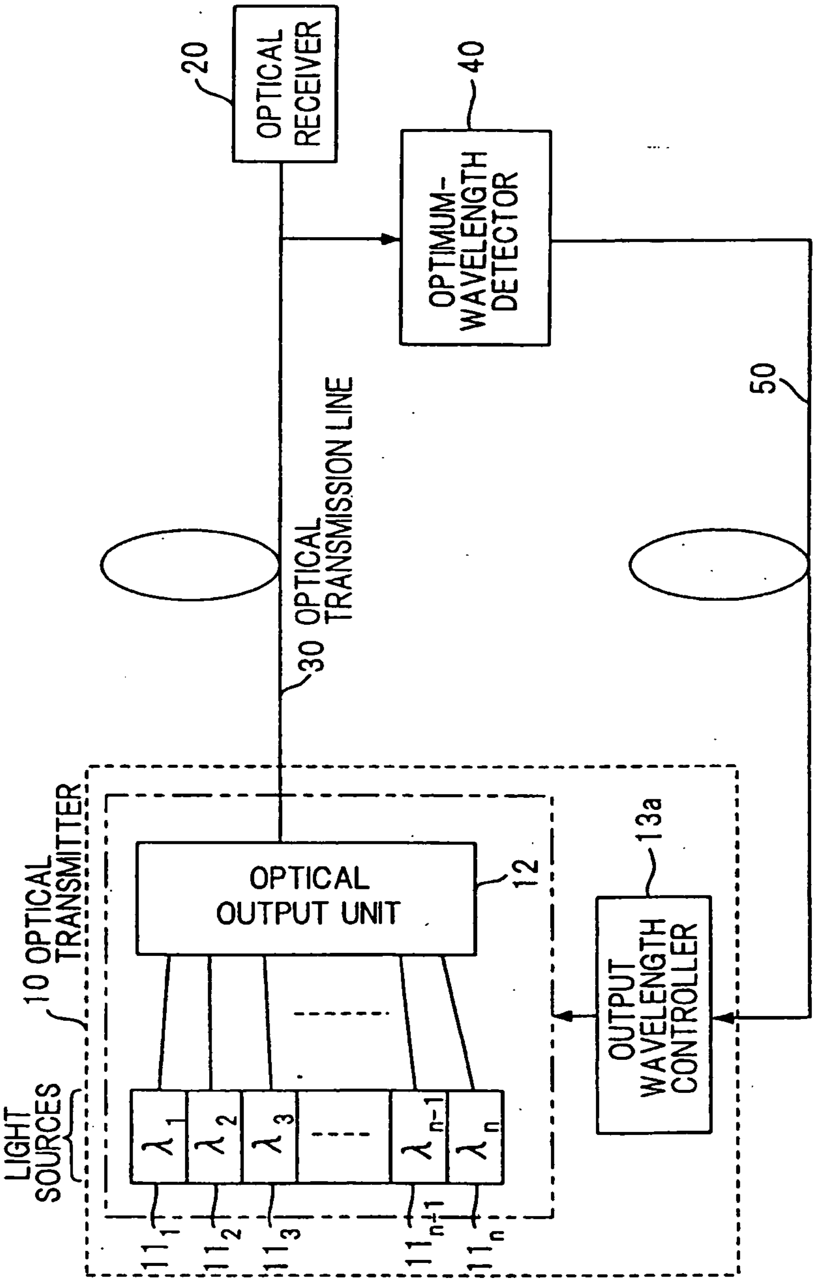

20
OPTICAL RECEIVER
40
OPTIMUM-WAVELENGTH DETECTOR
30 OPTICAL TRANSMISSION LINE
50
10 OPTICAL TRANSMITTER
LIGHT SOURCES
OPTICAL OUTPUT UNIT
12
13a
OUTPUT WAVELENGTH CONTROLLER
λ1
λ2
λ3
λn-1
λn
11_1
11_2
11_3
11_n-1
11_n

FIG.2

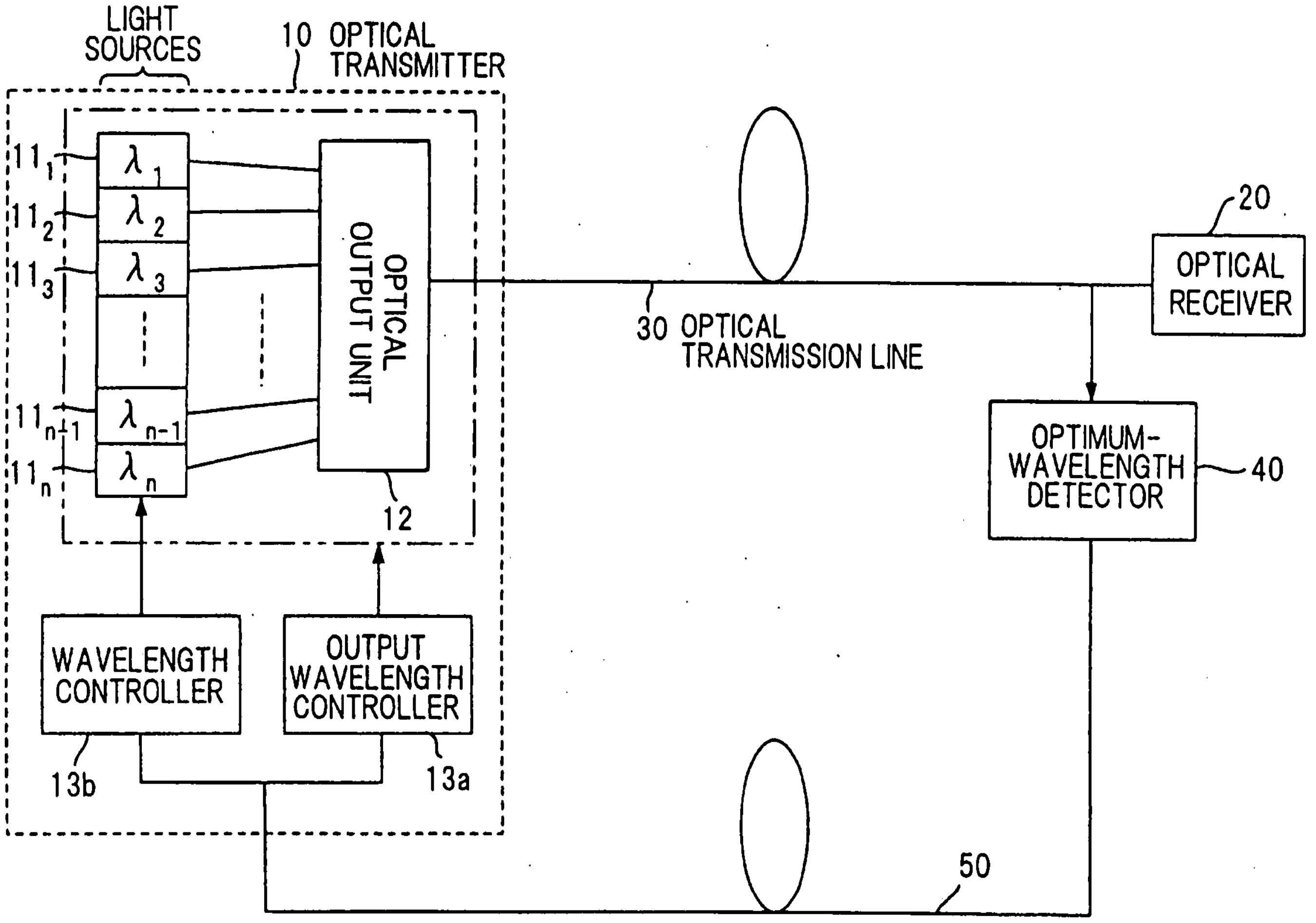

LIGHT SOURCES
10 OPTICAL TRANSMITTER
11_1
11_2
11_3
11_{n-1}
11_n
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
OPTICAL OUTPUT UNIT
12
WAVELENGTH CONTROLLER
13b
OUTPUT WAVELENGTH CONTROLLER
13a
30 OPTICAL TRANSMISSION LINE
20
OPTICAL RECEIVER
OPTIMUM-WAVELENGTH DETECTOR
40
50

FIG.3

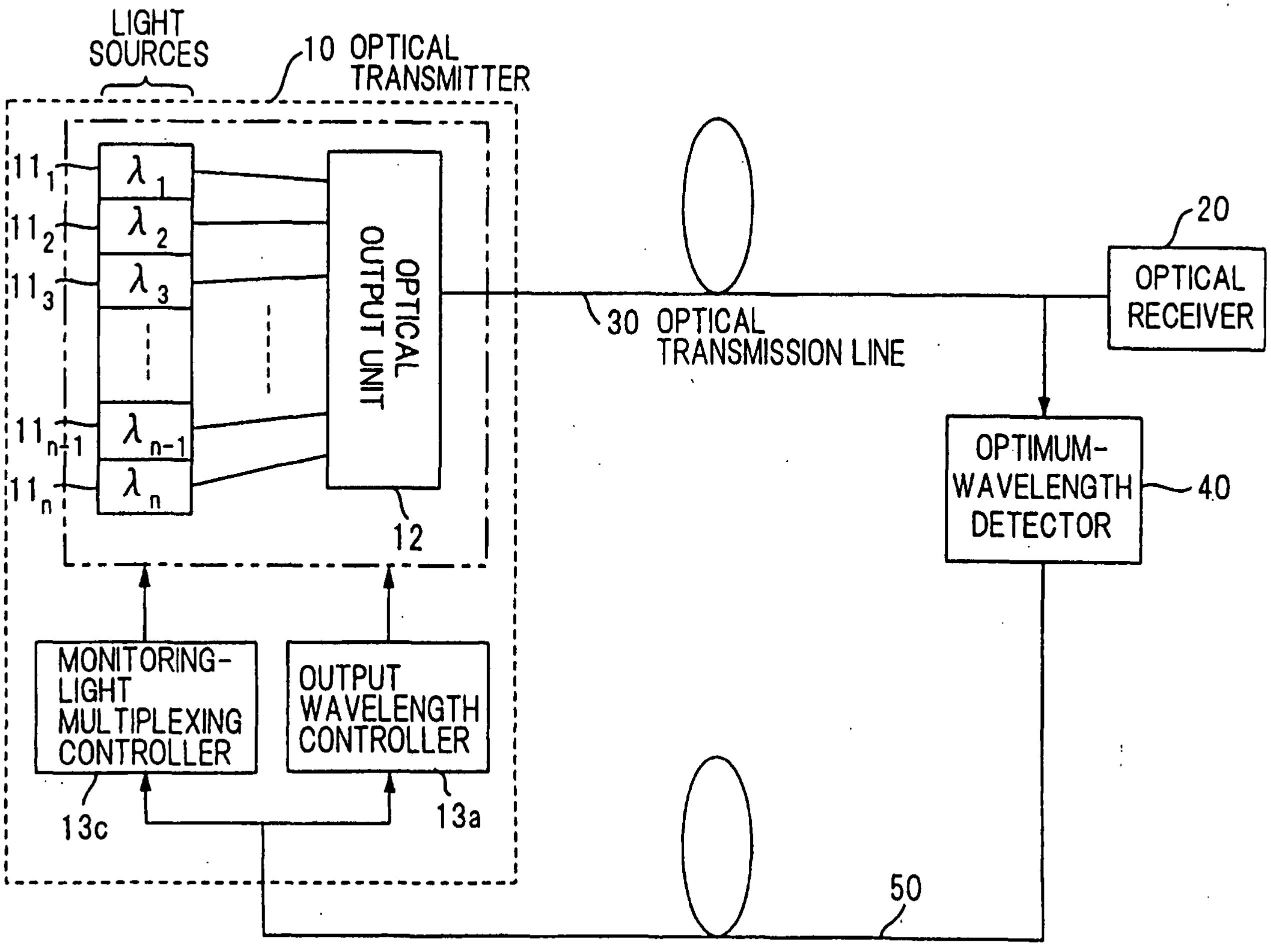
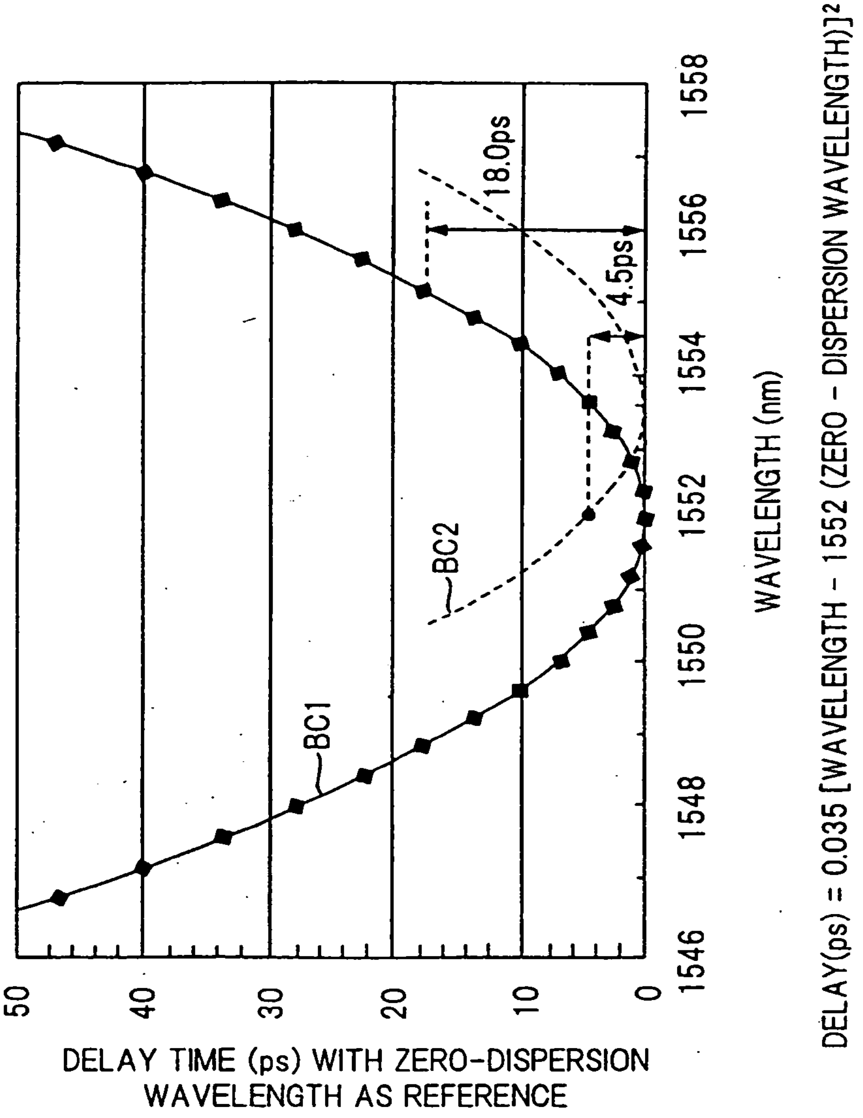

LIGHT SOURCES
10 OPTICAL TRANSMITTER
11_1
11_2
11_3
11_{n-1}
11_n
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
OPTICAL OUTPUT UNIT
12
MONITORING-LIGHT MULTIPLEXING CONTROLLER
13c
OUTPUT WAVELENGTH CONTROLLER
13a
30 OPTICAL TRANSMISSION LINE
20
OPTICAL RECEIVER
OPTIMUM-WAVELENGTH DETECTOR
40
50

FIG.4



DELAY(ps) = 0.035 [WAVELENGTH - 1552 (ZERO - DISPERSION WAVELENGTH)]^2

FIG.5A

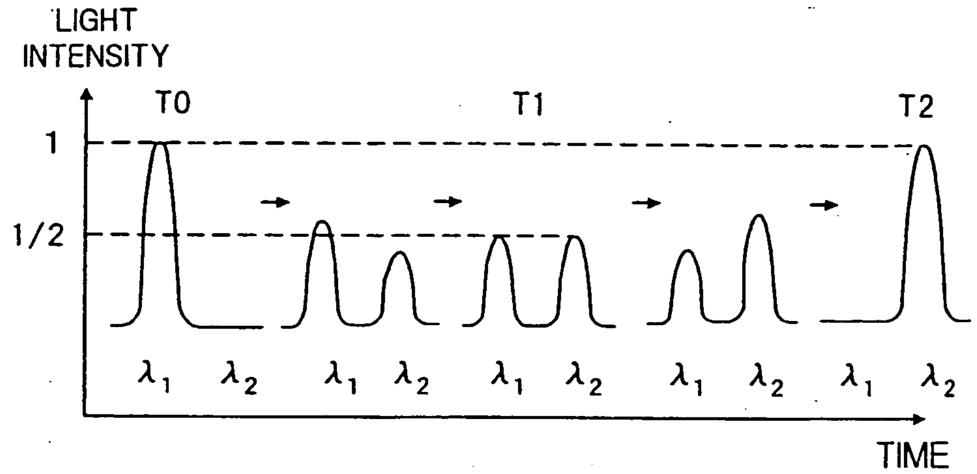

LIGHT
INTENSITY
T0
T1
T2
1
1/2
λ1
λ2
λ1
λ2
λ1
λ2
λ1
λ2
λ1
λ2
TIME

FIG.5B

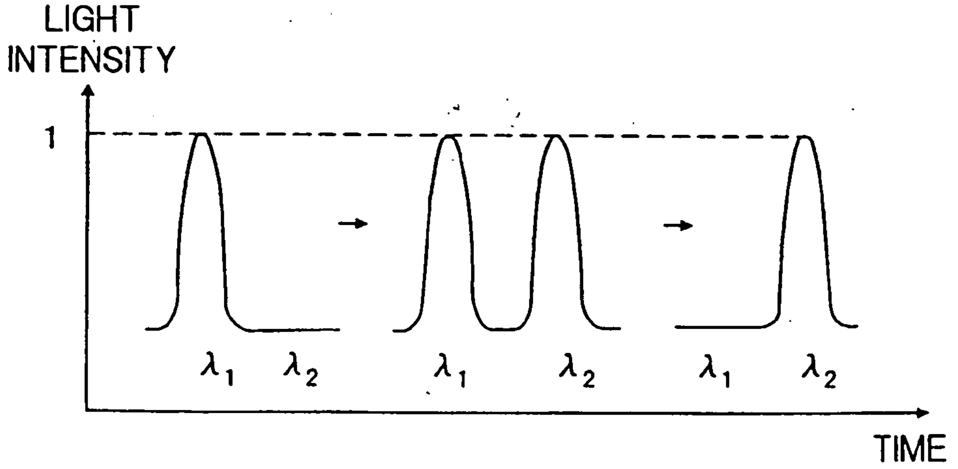

LIGHT
INTENSITY
1
λ1
λ2
λ1
λ2
λ1
λ2
TIME

FIG.6

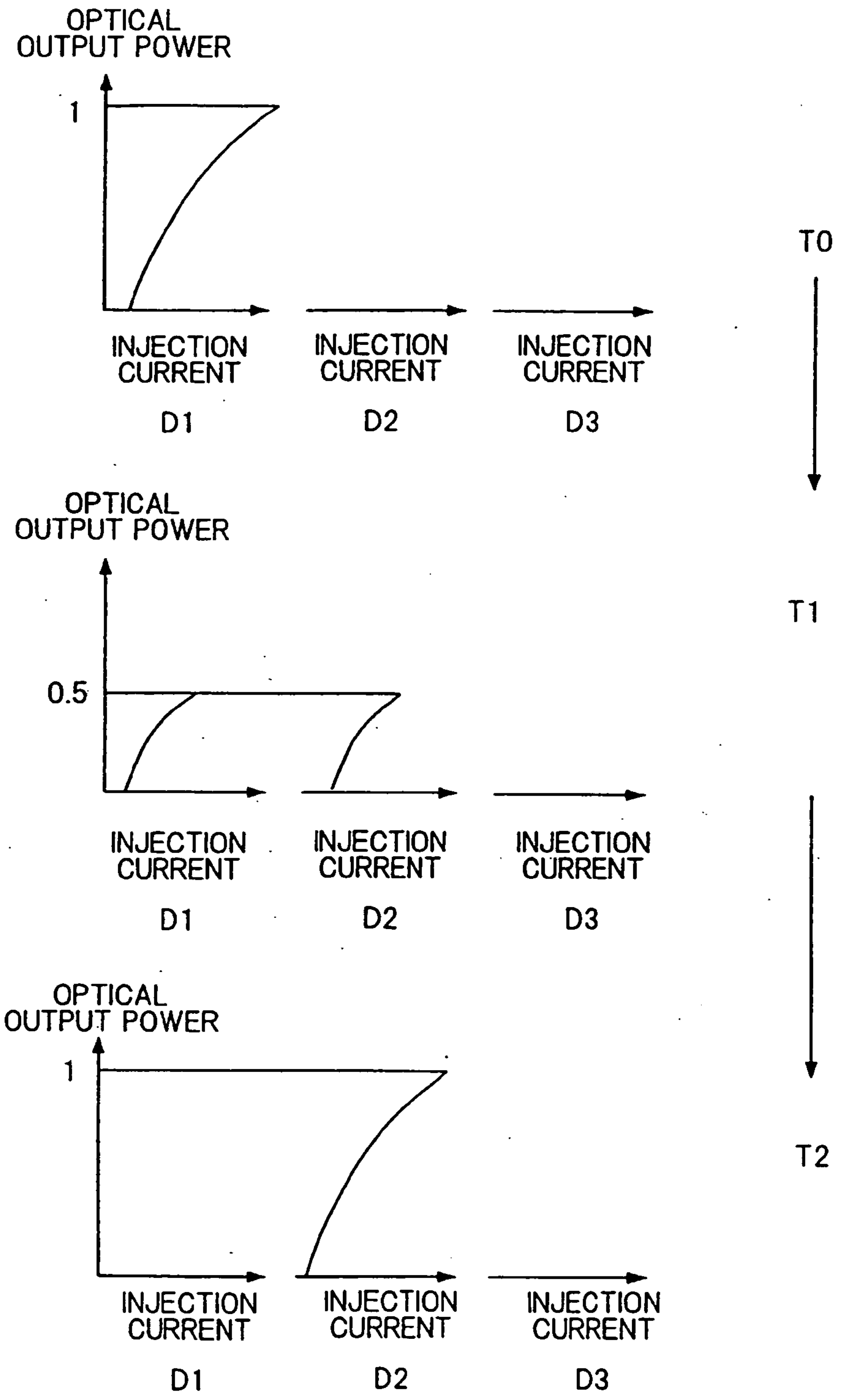

OPTICAL OUTPUT POWER
1
INJECTION CURRENT
INJECTION CURRENT
INJECTION CURRENT
D1
D2
D3
T0
OPTICAL OUTPUT POWER
0.5
INJECTION CURRENT
INJECTION CURRENT
INJECTION CURRENT
D1
D2
D3
T1
OPTICAL OUTPUT POWER
1
INJECTION CURRENT
INJECTION CURRENT
INJECTION CURRENT
D1
D2
D3
T2

FIG. 7

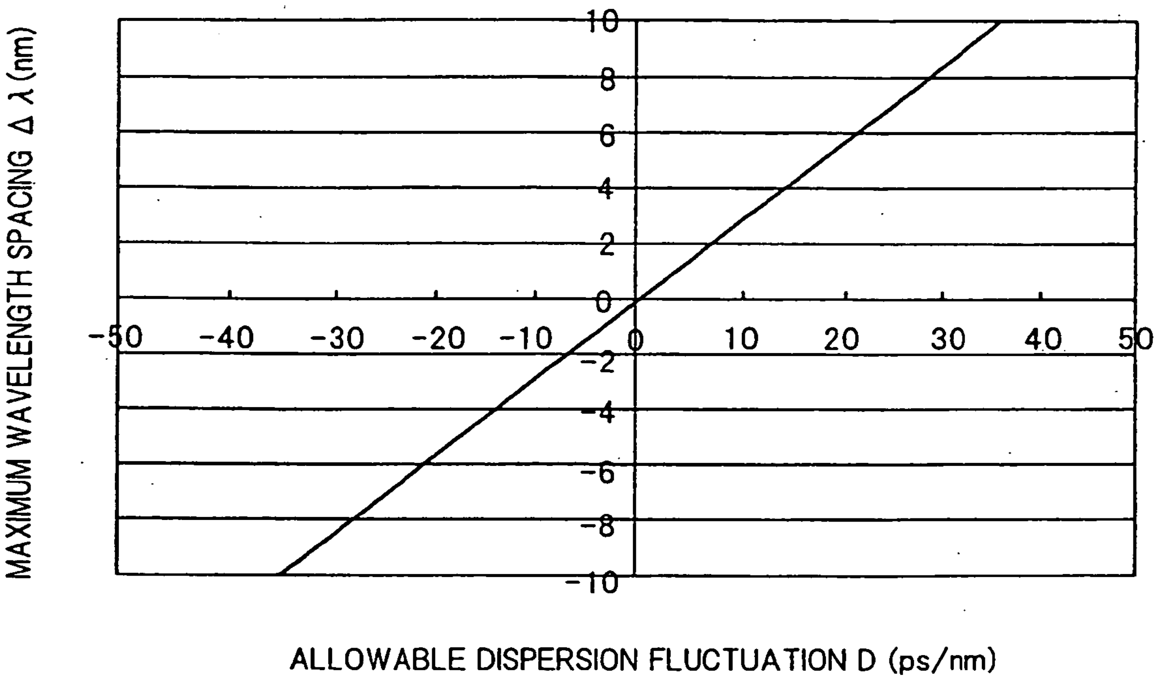

MAXIMUM WAVELENGTH SPACING Δ λ (nm)
10
8
6
4
2
0
-2
-4
-6
-8
-10
-50
-40
-30
-20
-10
0
10
20
30
40
50
ALLOWABLE DISPERSION FLUCTUATION D (ps/nm)

FIG.8

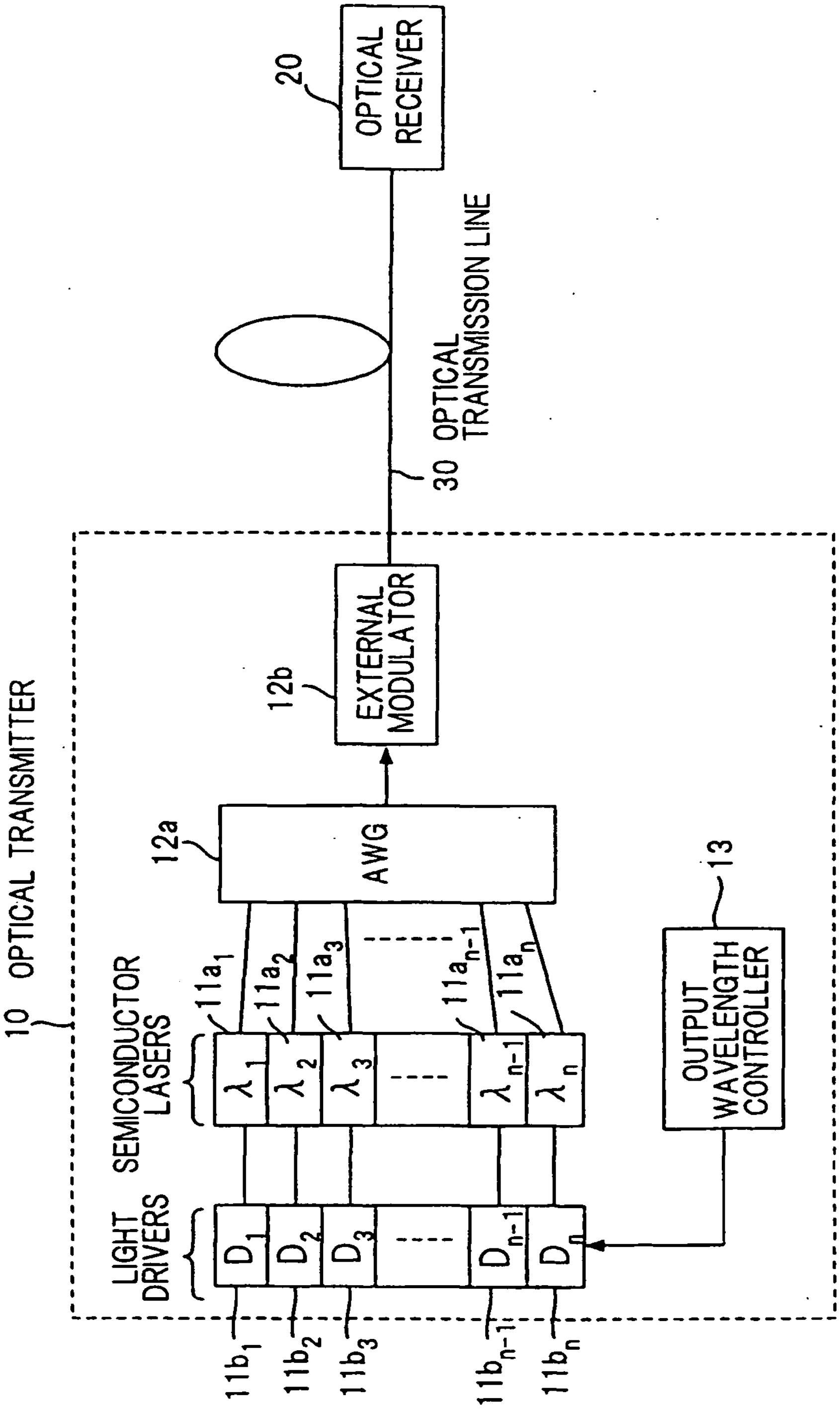

10 OPTICAL TRANSMITTER
LIGHT DRIVERS
SEMICONDUCTOR LASERS
D1
D2
D3
Dn-1
Dn
λ1
λ2
λ3
λn-1
λn
11b1
11b2
11b3
11bn-1
11bn
11a1
11a2
11a3
11an-1
11an
12a
AWG
12b
EXTERNAL MODULATOR
13
OUTPUT WAVELENGTH CONTROLLER
30 OPTICAL TRANSMISSION LINE
20
OPTICAL RECEIVER

FIG.9

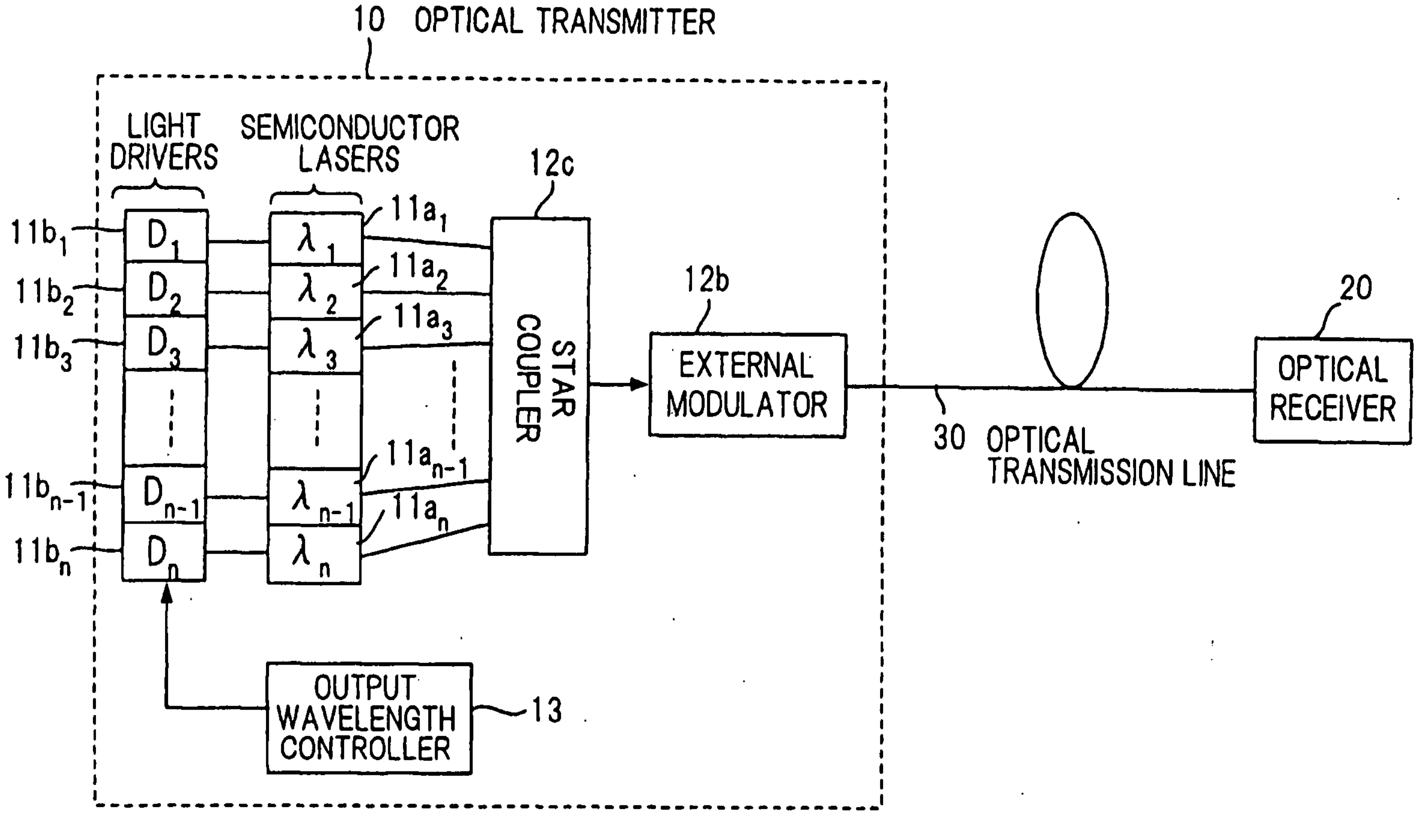

10 OPTICAL TRANSMITTER
LIGHT DRIVERS
SEMICONDUCTOR LASERS
12c
$11b_1$
$11b_2$
$11b_3$
$11b_{n-1}$
$11b_n$
D_1
D_2
D_3
D_{n-1}
D_n
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
$11a_1$
$11a_2$
$11a_3$
$11a_{n-1}$
$11a_n$
STAR COUPLER
12b
EXTERNAL MODULATOR
OUTPUT WAVELENGTH CONTROLLER
13
30 OPTICAL TRANSMISSION LINE
20
OPTICAL RECEIVER

FIG. 10A

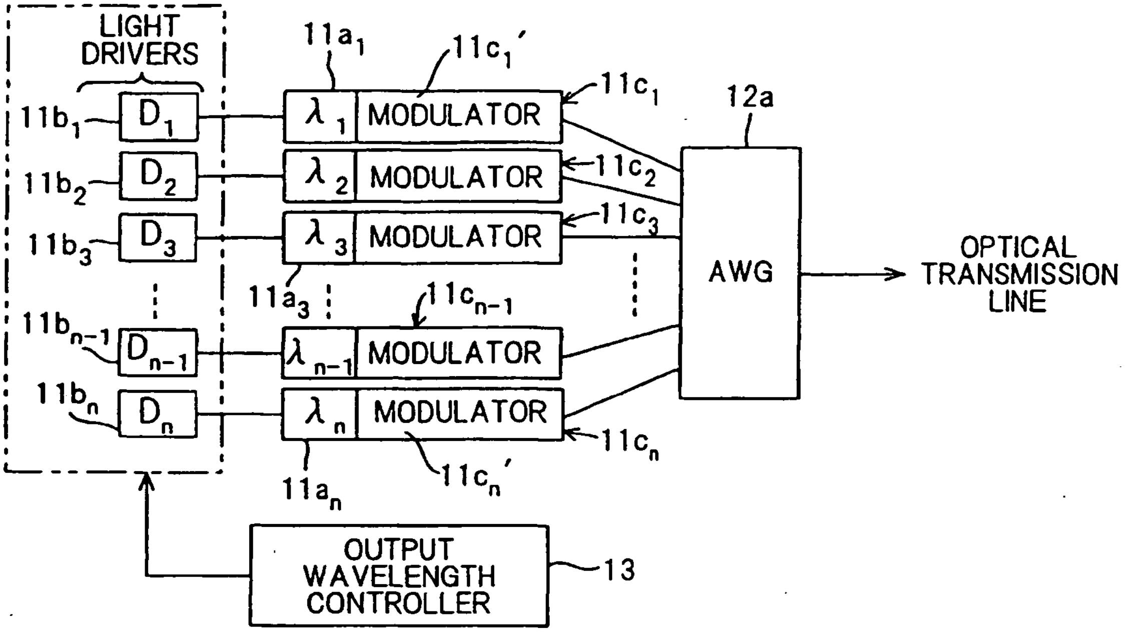

LIGHT DRIVERS
11b1
11b2
11b3
11bn-1
11bn
D1
D2
D3
Dn-1
Dn
11a1
11c1'
11c1
12a
λ1 MODULATOR
λ2 MODULATOR
11c2
λ3 MODULATOR
11c3
11a3
11cn-1
λn-1 MODULATOR
λn MODULATOR
11cn
11an
11cn'
AWG
OPTICAL TRANSMISSION LINE
OUTPUT WAVELENGTH CONTROLLER
13

FIG. 10B

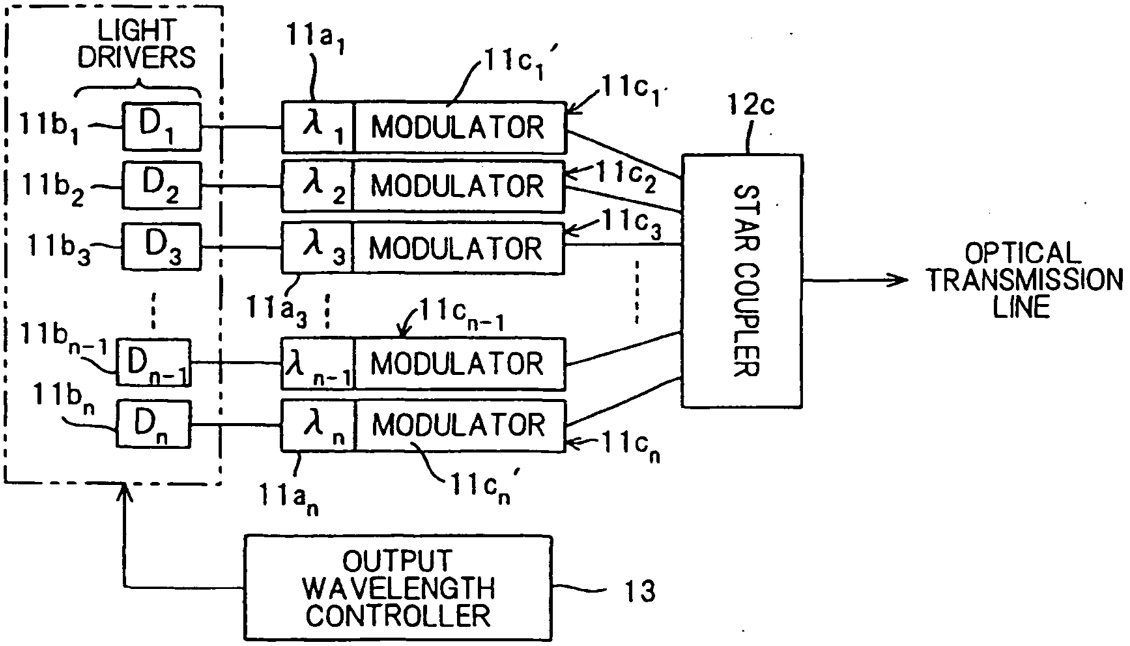

LIGHT DRIVERS
11b1
11b2
11b3
11bn-1
11bn
D1
D2
D3
Dn-1
Dn
11a1
11c1'
11c1
12c
λ1 MODULATOR
λ2 MODULATOR
11c2
λ3 MODULATOR
11c3
11a3
11cn-1
λn-1 MODULATOR
λn MODULATOR
11cn
11an
11cn'
STAR COUPLER
OPTICAL TRANSMISSION LINE
OUTPUT WAVELENGTH CONTROLLER
13

FIG.11

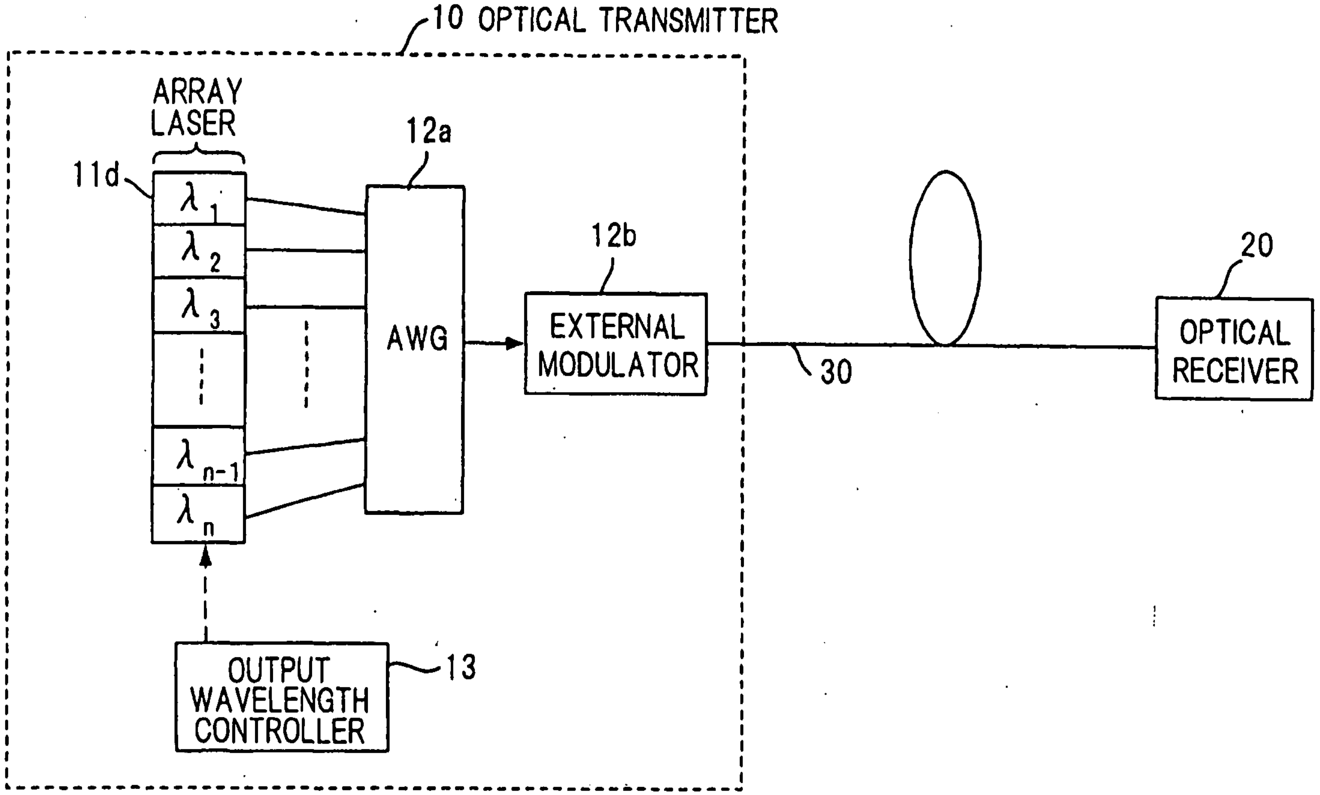

10 OPTICAL TRANSMITTER
ARRAY LASER
11d
λ 1
λ 2
λ 3
λ n-1
λ n
12a
AWG
12b
EXTERNAL MODULATOR
30
20
OPTICAL RECEIVER
OUTPUT WAVELENGTH CONTROLLER
13

FIG.12

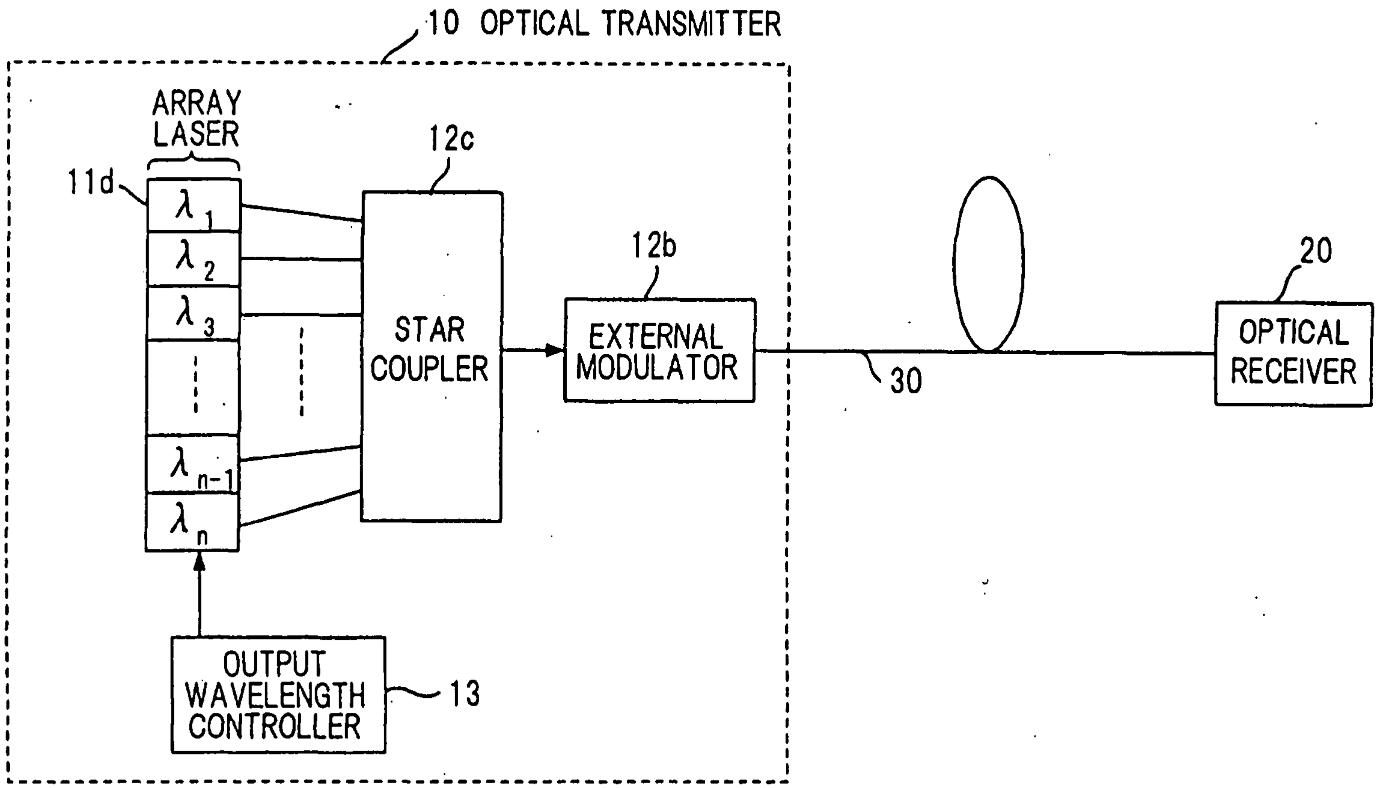

10 OPTICAL TRANSMITTER
ARRAY LASER
11d
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
12c
STAR COUPLER
12b
EXTERNAL MODULATOR
30
20
OPTICAL RECEIVER
OUTPUT WAVELENGTH CONTROLLER
13

FIG. 13

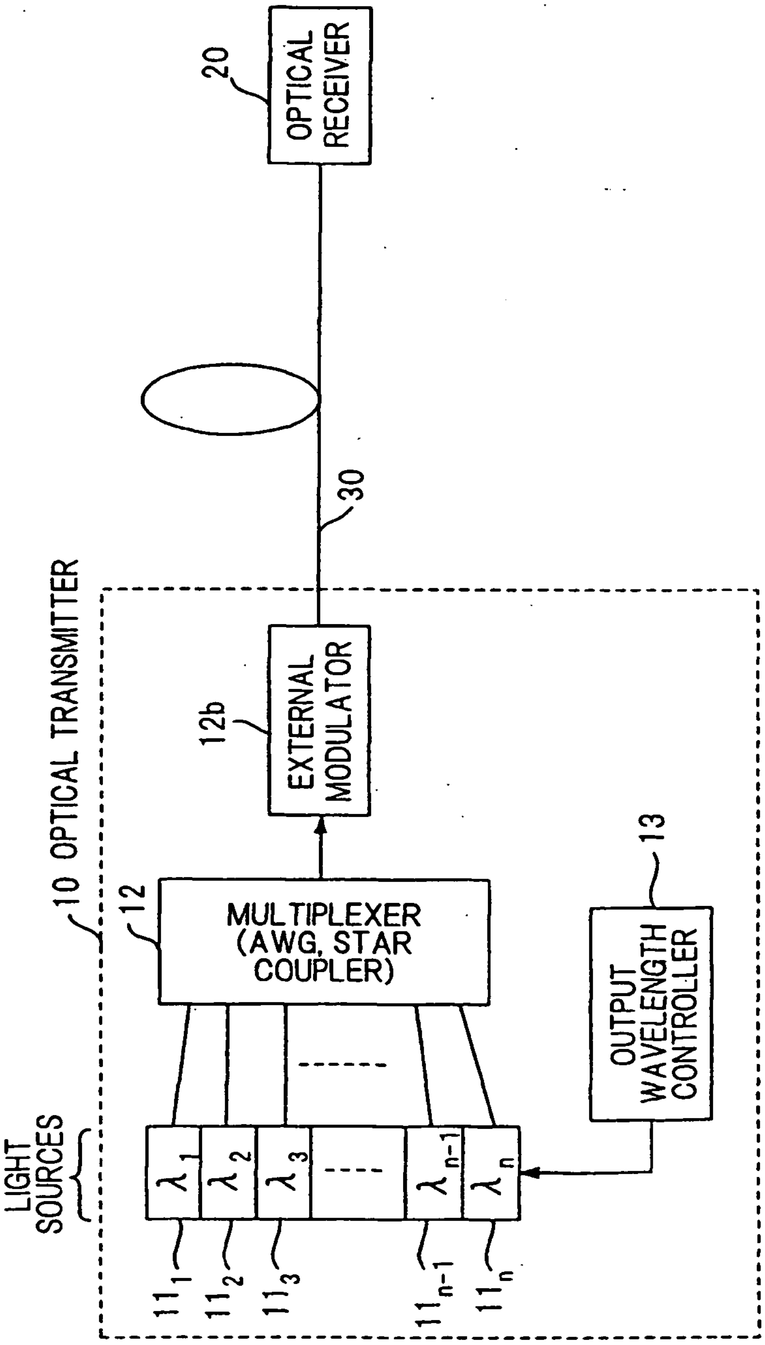

10 OPTICAL TRANSMITTER
LIGHT SOURCES
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
11_1
11_2
11_3
11_{n-1}
11_n
12
MULTIPLEXER (AWG, STAR COUPLER)
12b
EXTERNAL MODULATOR
13
OUTPUT WAVELENGTH CONTROLLER
30
20
OPTICAL RECEIVER

FIG.14

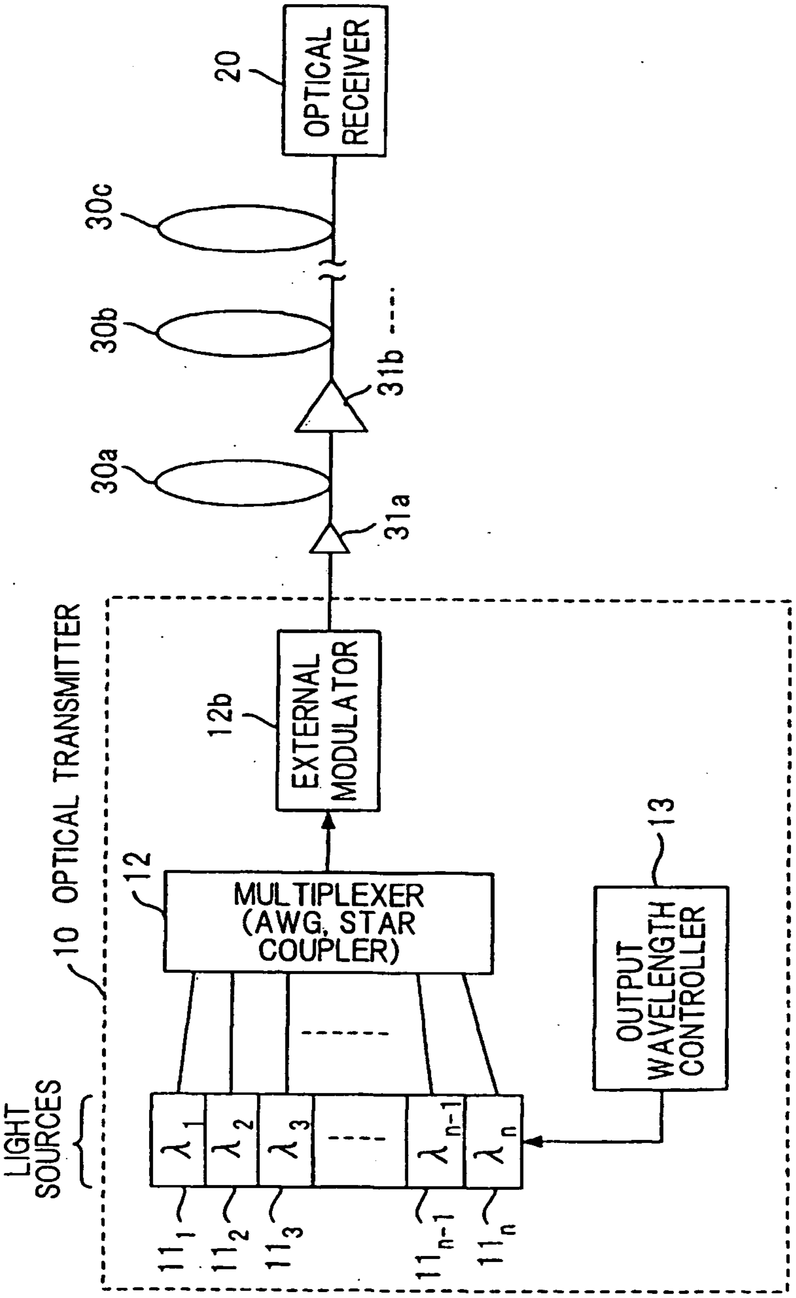

20
OPTICAL RECEIVER
30a
30b
30c
31a
31b
10 OPTICAL TRANSMITTER
12b
EXTERNAL MODULATOR
12
MULTIPLEXER (AWG, STAR COUPLER)
13
OUTPUT WAVELENGTH CONTROLLER
LIGHT SOURCES
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
11_1
11_2
11_3
11_{n-1}
11_n

FIG. 15

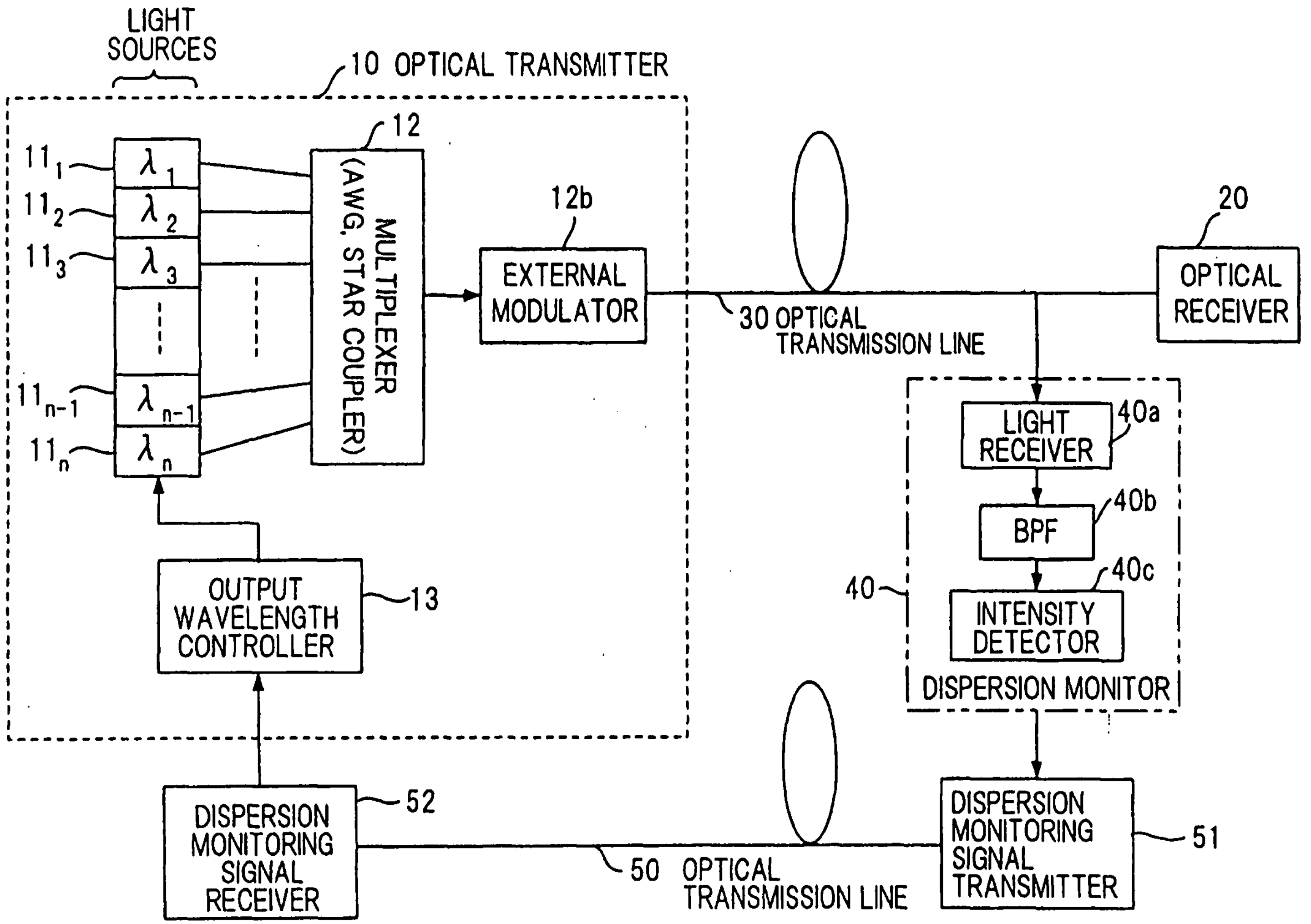

LIGHT SOURCES
10 OPTICAL TRANSMITTER
11_1
11_2
11_3
11_{n-1}
11_n
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
12
MULTIPLEXER (AWG, STAR COUPLER)
12b
EXTERNAL MODULATOR
30 OPTICAL TRANSMISSION LINE
20
OPTICAL RECEIVER
40a
LIGHT RECEIVER
40b
BPF
40c
INTENSITY DETECTOR
40
DISPERSION MONITOR
OUTPUT WAVELENGTH CONTROLLER
13
52
DISPERSION MONITORING SIGNAL RECEIVER
50 OPTICAL TRANSMISSION LINE
DISPERSION MONITORING SIGNAL TRANSMITTER
51

FIG.16

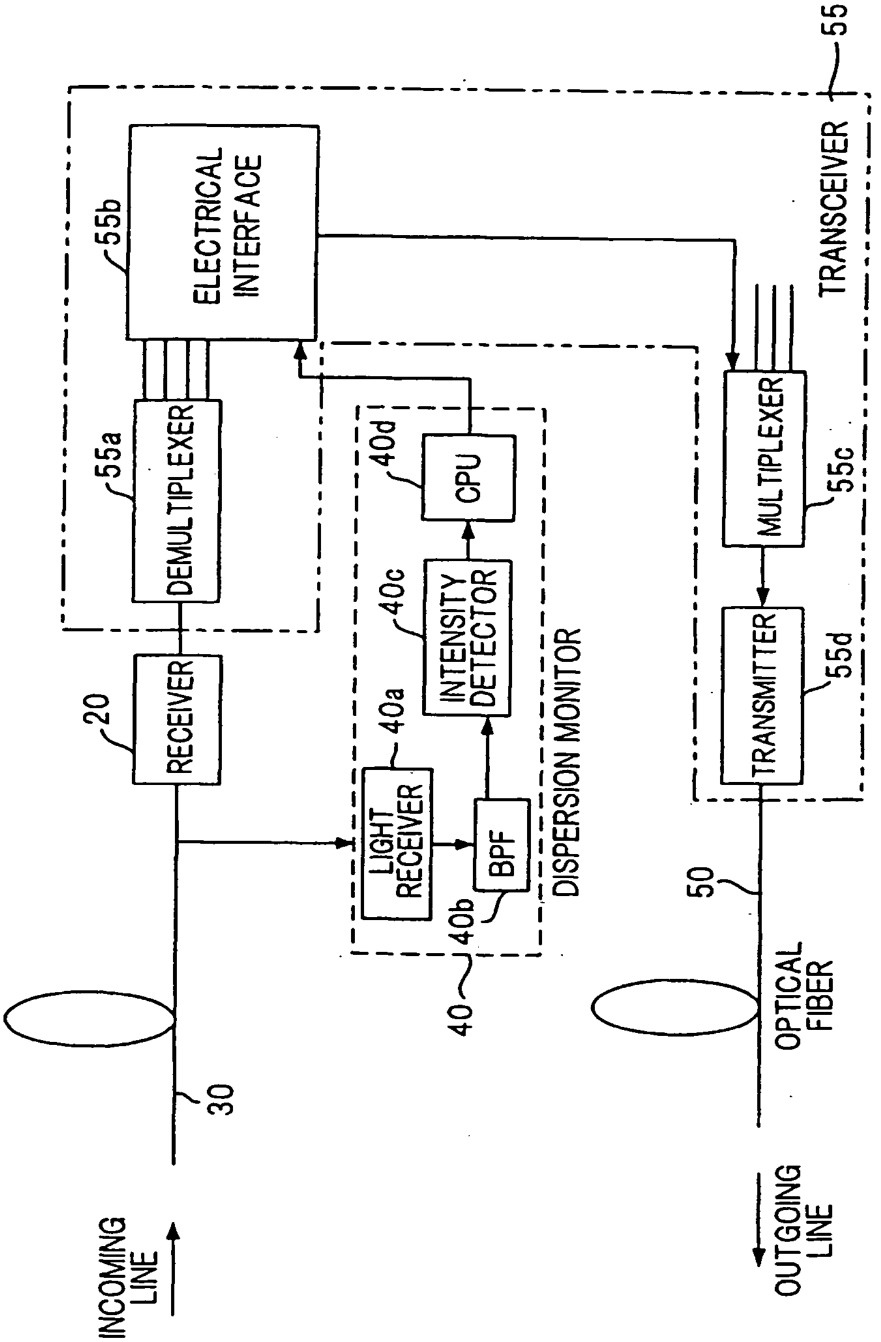

INCOMING LINE
30
20
RECEIVER
55a
DEMULTIPLEXER
55b
ELECTRICAL INTERFACE
LIGHT RECEIVER
40a
BPF
40b
INTENSITY DETECTOR
40c
CPU
40d
DISPERSION MONITOR
40
MULTIPLEXER
55c
TRANSMITTER
55d
TRANSCEIVER
55
50
OPTICAL FIBER
OUTGOING LINE

FIG.17

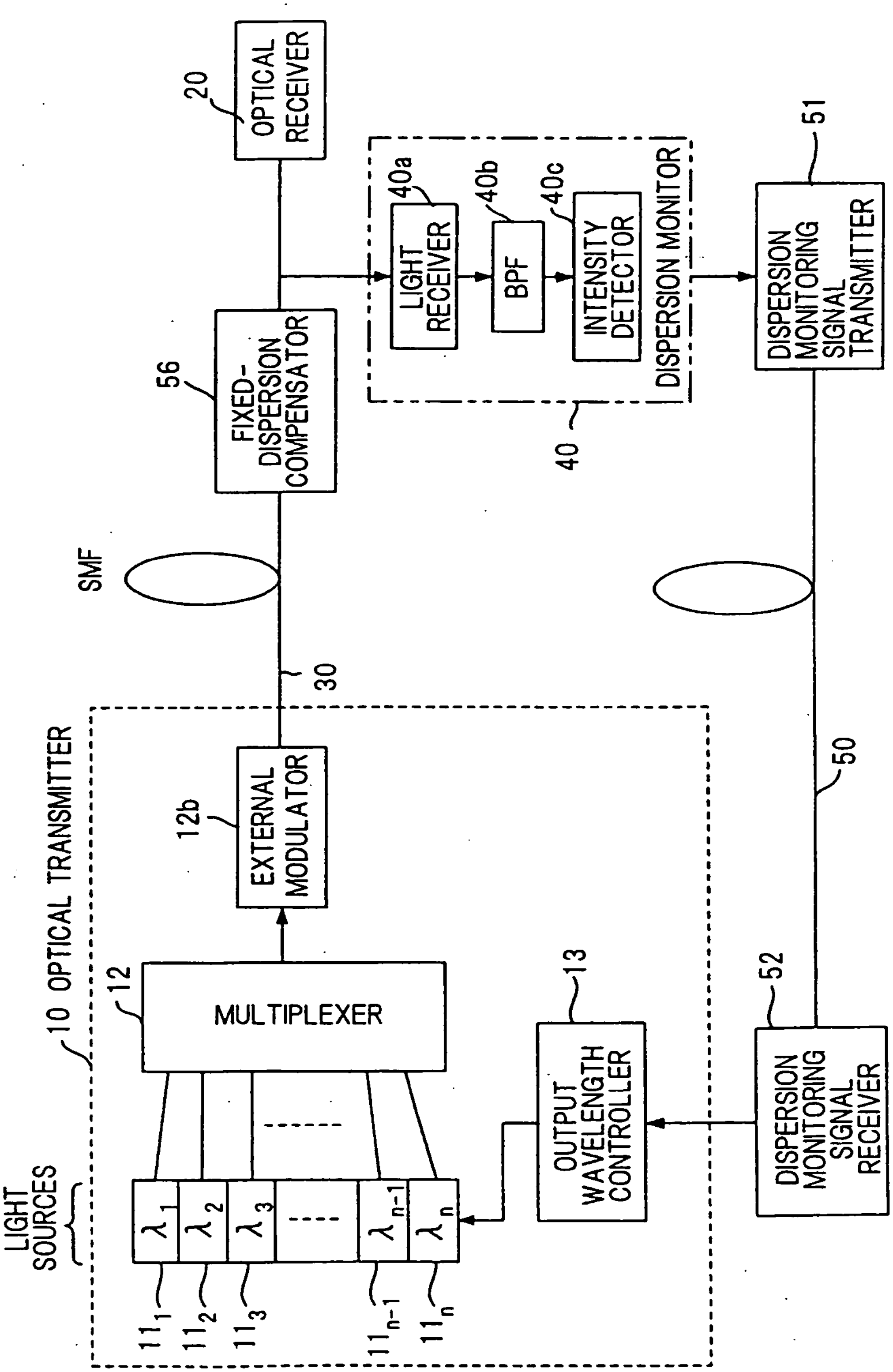

10 OPTICAL TRANSMITTER
LIGHT SOURCES
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
11_1
11_2
11_3
11_{n-1}
11_n
12
MULTIPLEXER
13
OUTPUT WAVELENGTH CONTROLLER
12b
EXTERNAL MODULATOR
30
SMF
56
FIXED-DISPERSION COMPENSATOR
20
OPTICAL RECEIVER
40
DISPERSION MONITOR
40a
LIGHT RECEIVER
40b
BPF
40c
INTENSITY DETECTOR
51
DISPERSION MONITORING SIGNAL TRANSMITTER
50
52
DISPERSION MONITORING SIGNAL RECEIVER

FIG.18

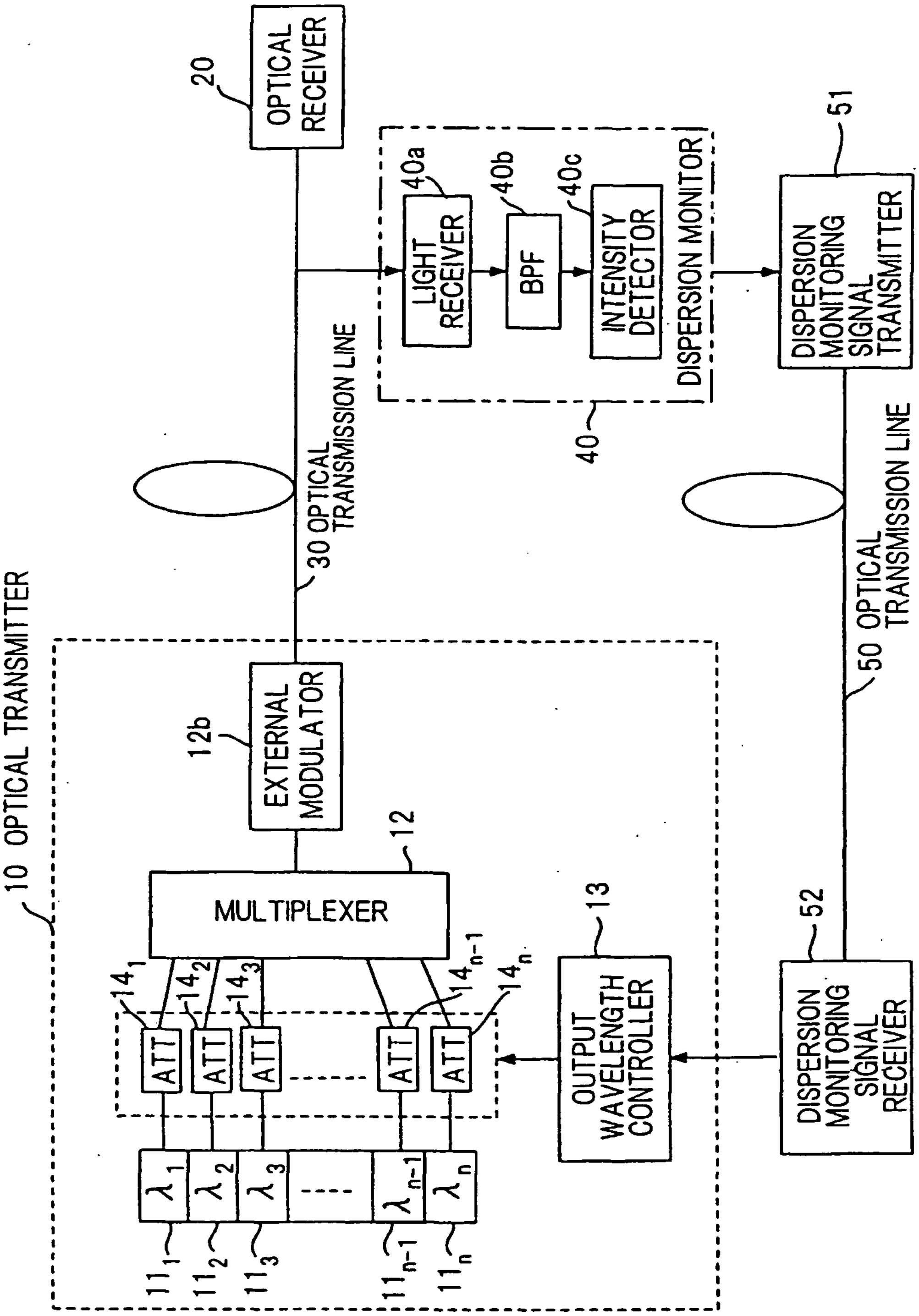

10 OPTICAL TRANSMITTER
11_1
11_2
11_3
11_{n-1}
11_n
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
ATT
ATT
ATT
ATT
ATT
14_1
14_2
14_3
14_{n-1}
14_n
MULTIPLEXER
12
13
OUTPUT WAVELENGTH CONTROLLER
12b
EXTERNAL MODULATOR
30 OPTICAL TRANSMISSION LINE
20
OPTICAL RECEIVER
40a
LIGHT RECEIVER
40b
BPF
40c
INTENSITY DETECTOR
DISPERSION MONITOR
40
51
DISPERSION MONITORING SIGNAL TRANSMITTER
50 OPTICAL TRANSMISSION LINE
52
DISPERSION MONITORING SIGNAL RECEIVER

FIG.19

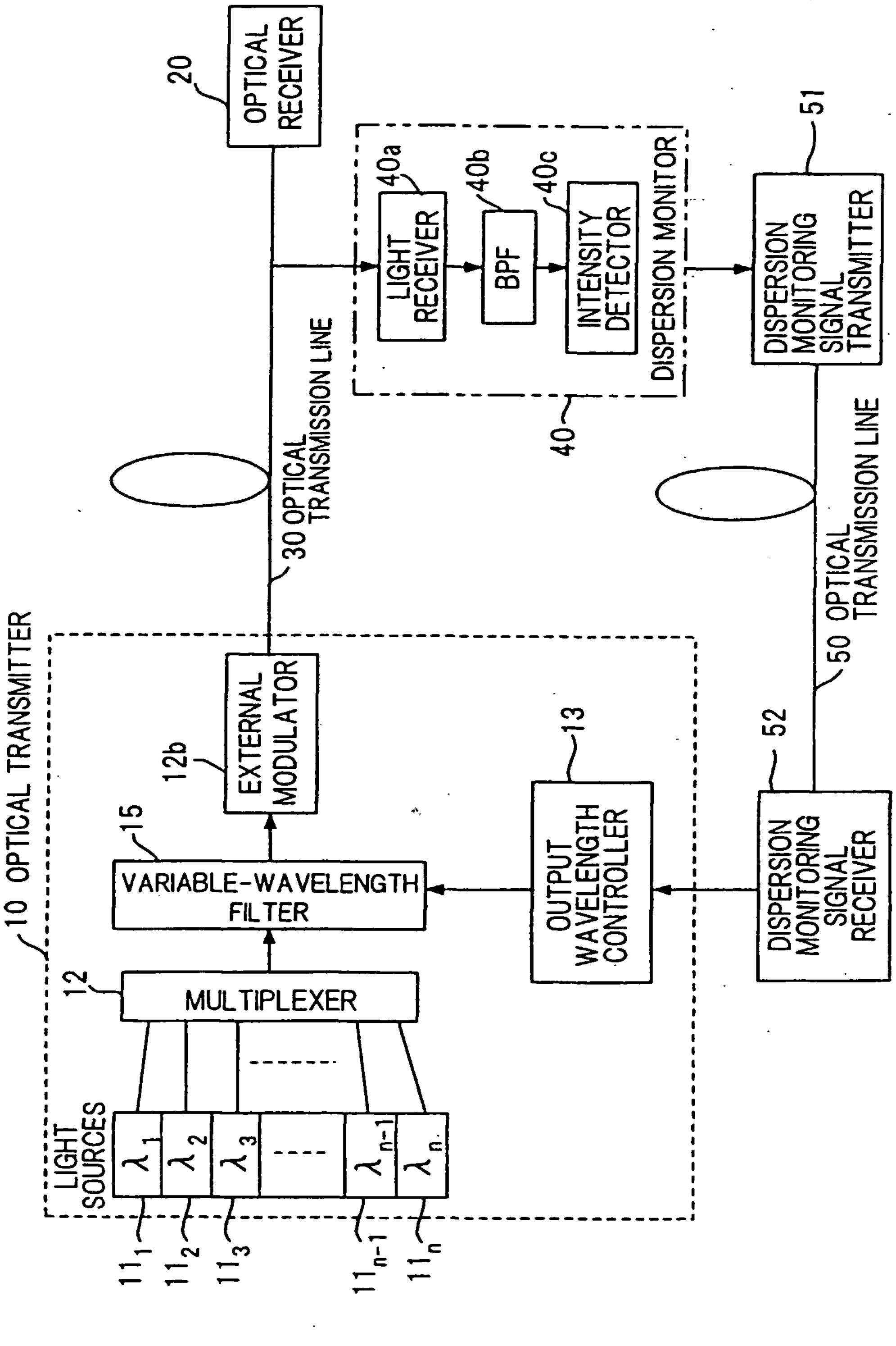

10 OPTICAL TRANSMITTER
LIGHT SOURCES
λ1
λ2
λ3
λn-1
λn
11_1
11_2
11_3
11_n-1
11_n
12
MULTIPLEXER
15
VARIABLE-WAVELENGTH FILTER
12b
EXTERNAL MODULATOR
13
OUTPUT WAVELENGTH CONTROLLER
30 OPTICAL TRANSMISSION LINE
20
OPTICAL RECEIVER
40
DISPERSION MONITOR
40a
LIGHT RECEIVER
40b
BPF
40c
INTENSITY DETECTOR
51
DISPERSION MONITORING SIGNAL TRANSMITTER
50 OPTICAL TRANSMISSION LINE
52
DISPERSION MONITORING SIGNAL RECEIVER

FIG.20

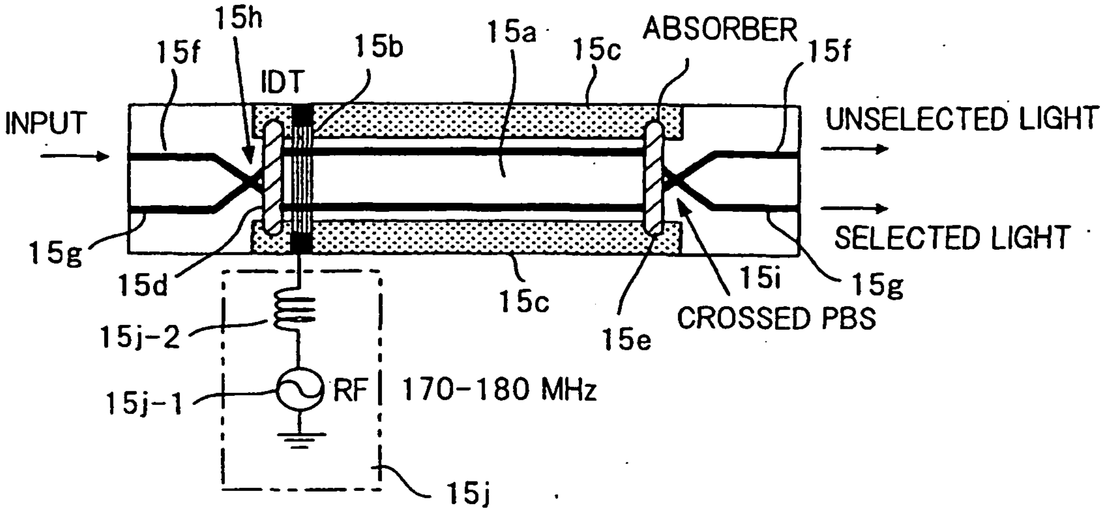

15h
15f
15b
15a
15c
ABSORBER
15f
IDT
INPUT
UNSELECTED LIGHT
SELECTED LIGHT
15g
15d
15c
15i
15g
CROSSED PBS
15e
15j-2
15j-1
RF
170-180 MHz
15j

FIG.21

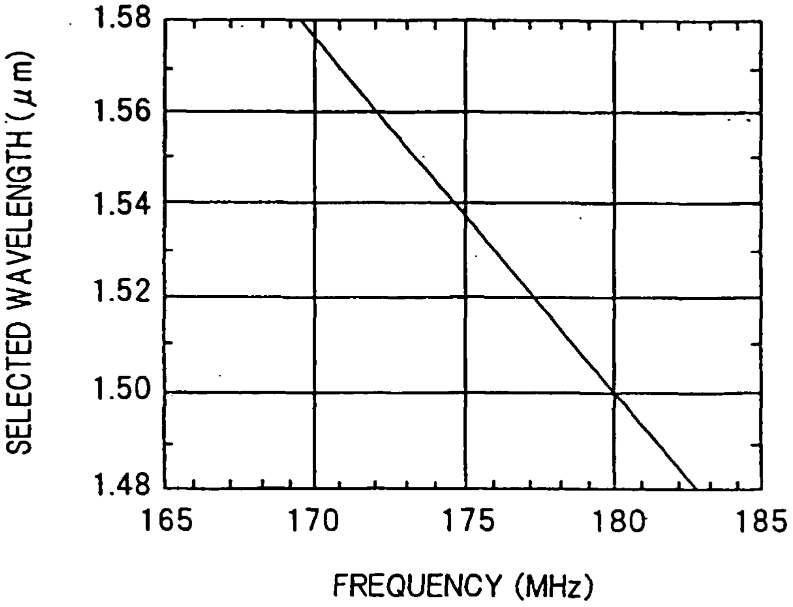

SELECTED WAVELENGTH (μm)
1.58
1.56
1.54
1.52
1.50
1.48
165
170
175
180
185
FREQUENCY (MHz)

FIG.22

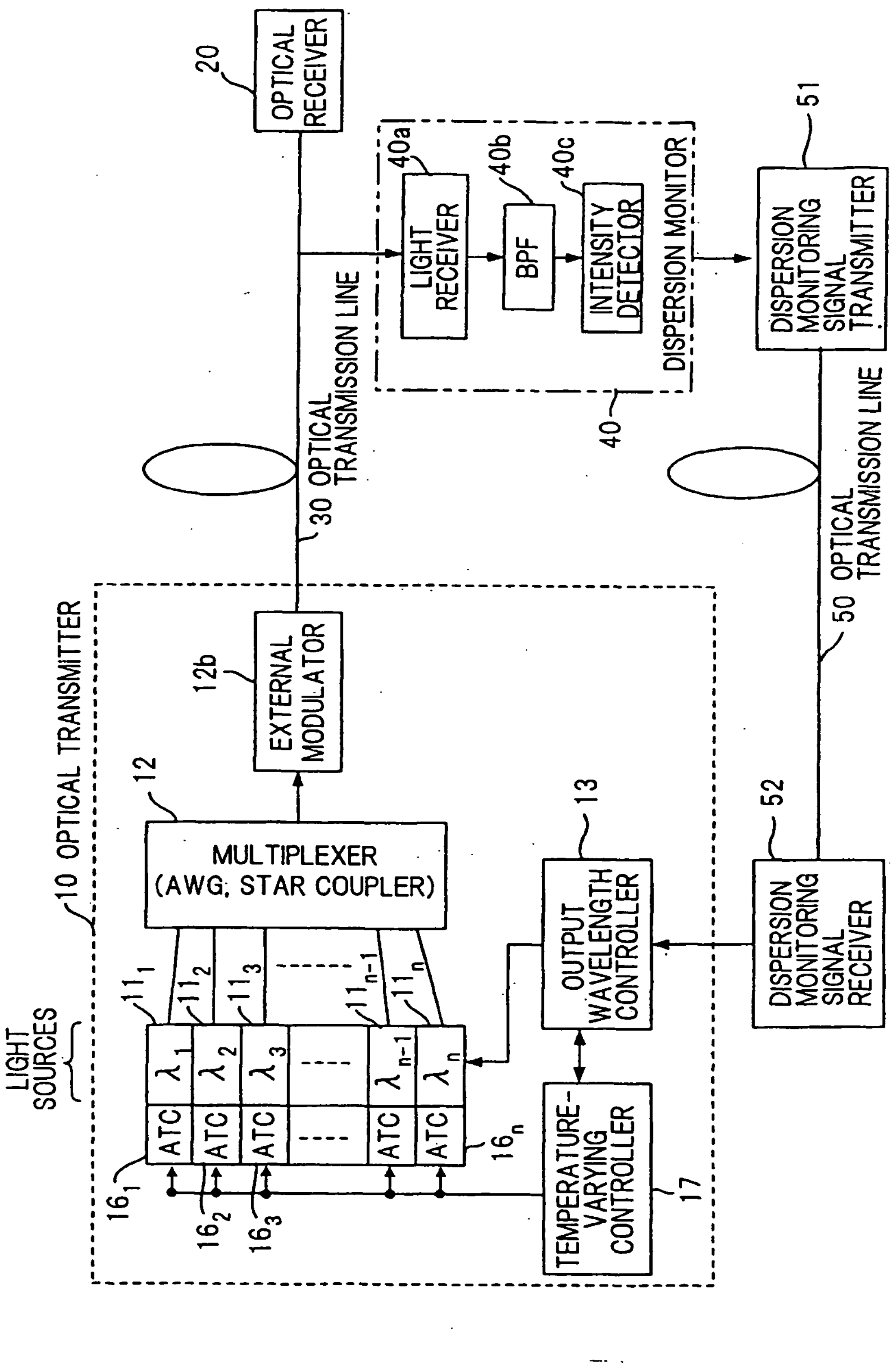

10 OPTICAL TRANSMITTER
LIGHT SOURCES
ATC
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
11_1
11_2
11_3
11_{n-1}
11_n
16_1
16_2
16_3
16_n
12
MULTIPLEXER (AWG; STAR COUPLER)
12b
EXTERNAL MODULATOR
13
OUTPUT WAVELENGTH CONTROLLER
17
TEMPERATURE-VARYING CONTROLLER
30 OPTICAL TRANSMISSION LINE
20
OPTICAL RECEIVER
40
40a
LIGHT RECEIVER
40b
BPF
40c
INTENSITY DETECTOR
DISPERSION MONITOR
51
DISPERSION MONITORING SIGNAL TRANSMITTER
50 OPTICAL TRANSMISSION LINE
52
DISPERSION MONITORING SIGNAL RECEIVER

FIG.23

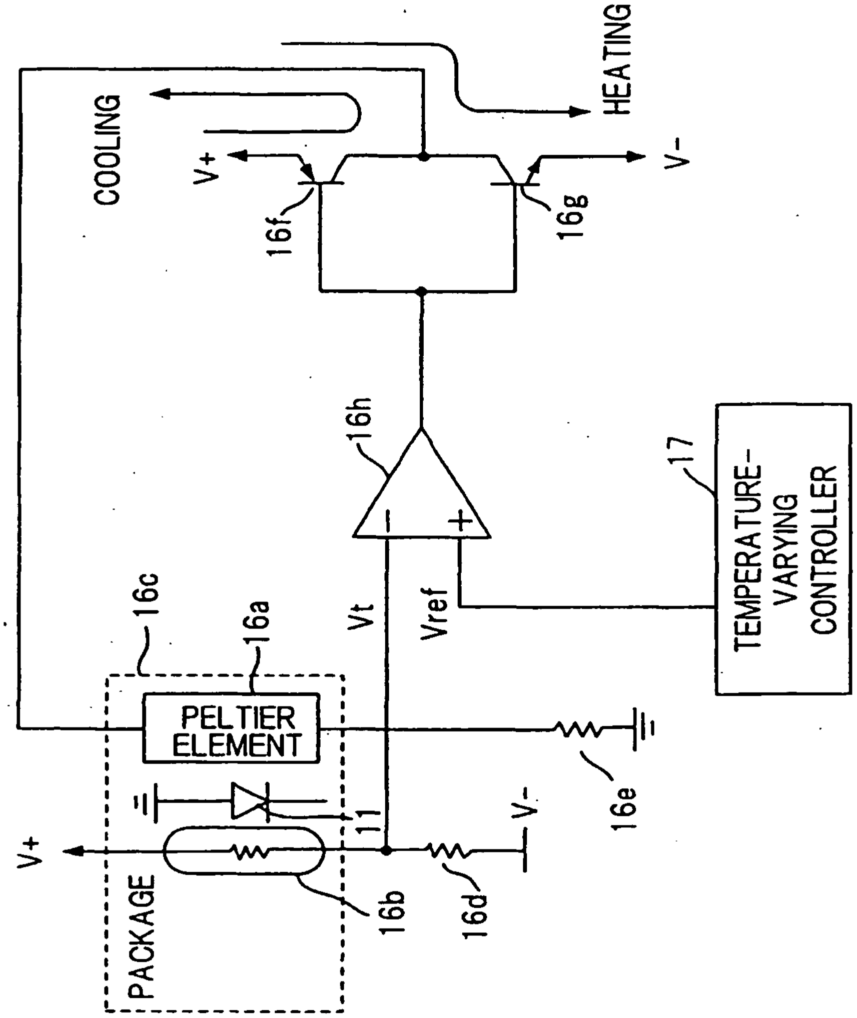

HEATING
COOLING
V+
V-
16f
16g
16h
17
TEMPERATURE-VARYING CONTROLLER
16c
16a
Vt
Vref
PELTIER ELEMENT
11
V-
16e
V+
PACKAGE
16b
16d

FIG.24

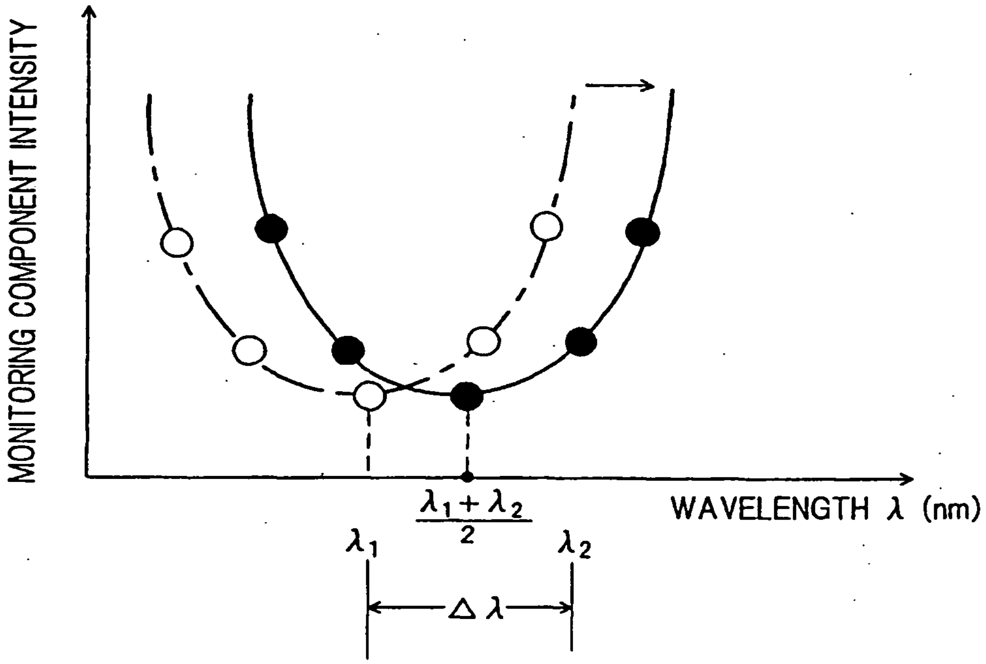

MONITORING COMPONENT INTENSITY
WAVELENGTH λ (nm)
λ1
$\frac{\lambda_1+\lambda_2}{2}$
λ2
Δλ

FIG.25

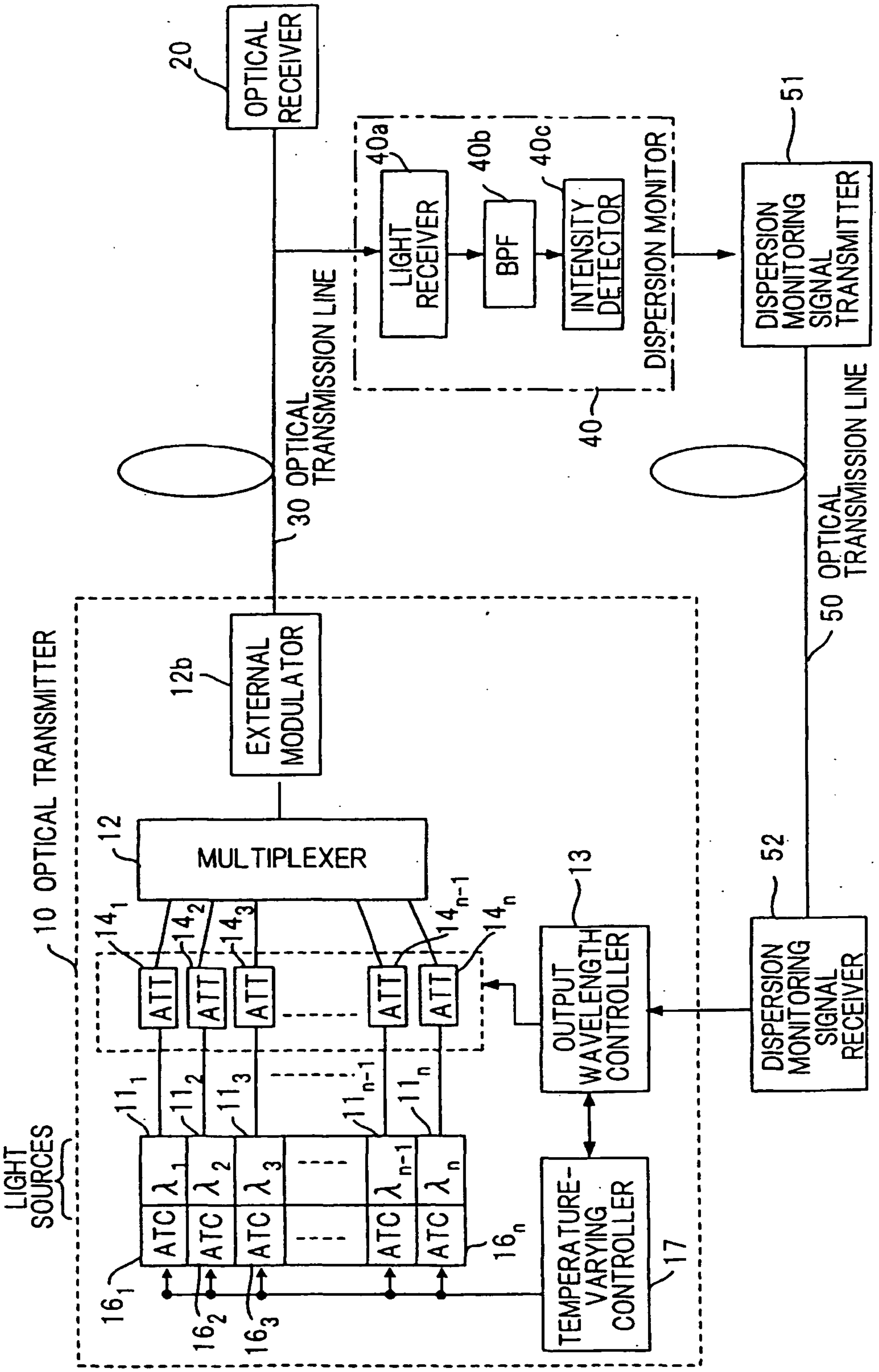

20
OPTICAL RECEIVER
30 OPTICAL TRANSMISSION LINE
40a
LIGHT RECEIVER
40b
BPF
40c
INTENSITY DETECTOR
DISPERSION MONITOR
40
51
DISPERSION MONITORING SIGNAL TRANSMITTER
50 OPTICAL TRANSMISSION LINE
10 OPTICAL TRANSMITTER
12b
EXTERNAL MODULATOR
12
MULTIPLEXER
13
OUTPUT WAVELENGTH CONTROLLER
52
DISPERSION MONITORING SIGNAL RECEIVER
14_1
14_2
14_3
14_{n-1}
14_n
ATT
11_1
11_2
11_3
11_{n-1}
11_n
LIGHT SOURCES
ATC
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
16_1
16_2
16_3
16_n
17
TEMPERATURE-VARYING CONTROLLER

FIG.26

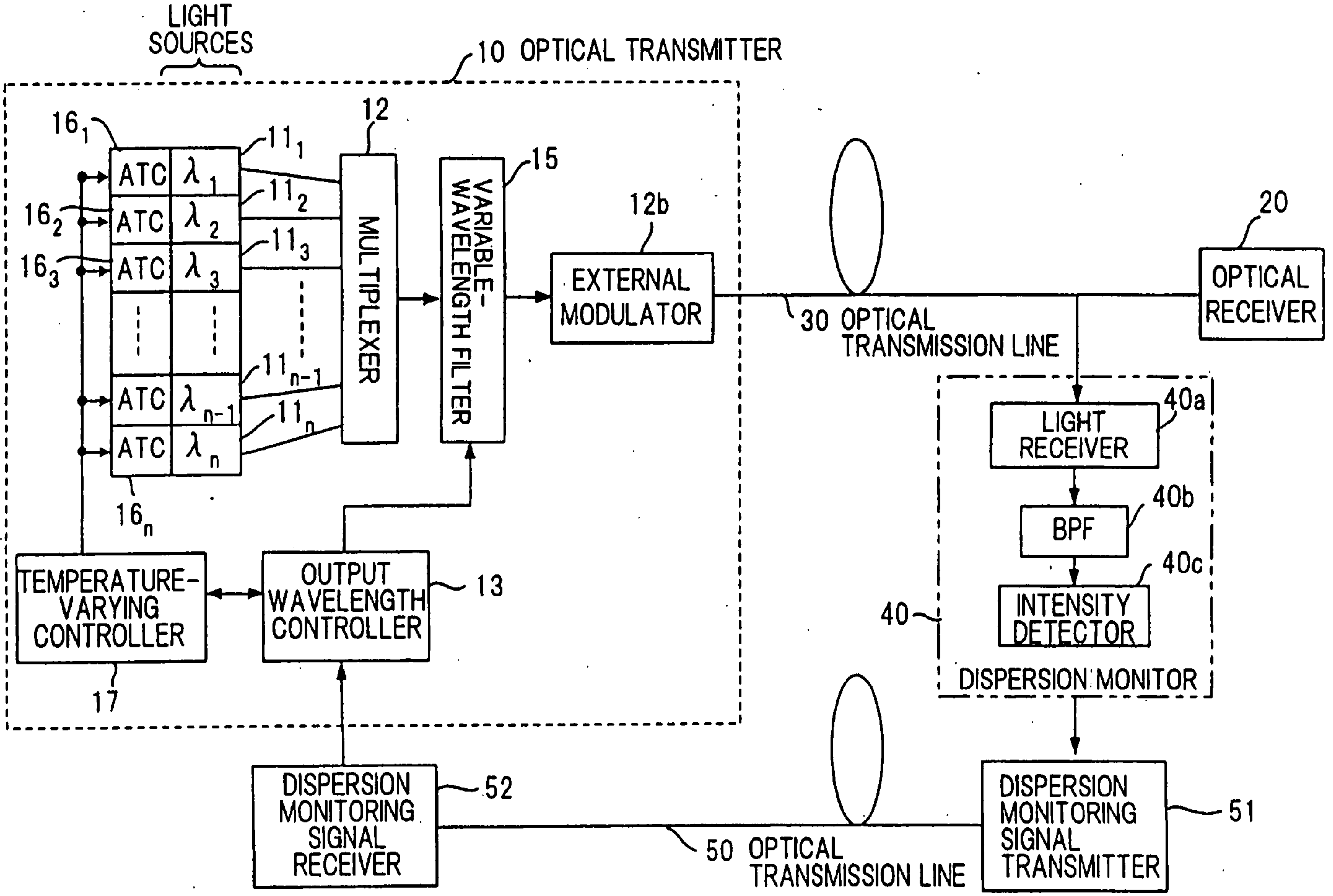

LIGHT SOURCES
10 OPTICAL TRANSMITTER
16_1
16_2
16_3
16_n
ATC
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
11_1
11_2
11_3
11_{n-1}
11_n
12
MULTIPLEXER
15
VARIABLE-WAVELENGTH FILTER
12b
EXTERNAL MODULATOR
TEMPERATURE-VARYING CONTROLLER
17
OUTPUT WAVELENGTH CONTROLLER
13
30 OPTICAL TRANSMISSION LINE
20
OPTICAL RECEIVER
40a
LIGHT RECEIVER
40b
BPF
40c
INTENSITY DETECTOR
40
DISPERSION MONITOR
DISPERSION MONITORING SIGNAL RECEIVER
52
50 OPTICAL TRANSMISSION LINE
DISPERSION MONITORING SIGNAL TRANSMITTER
51

FIG.27A

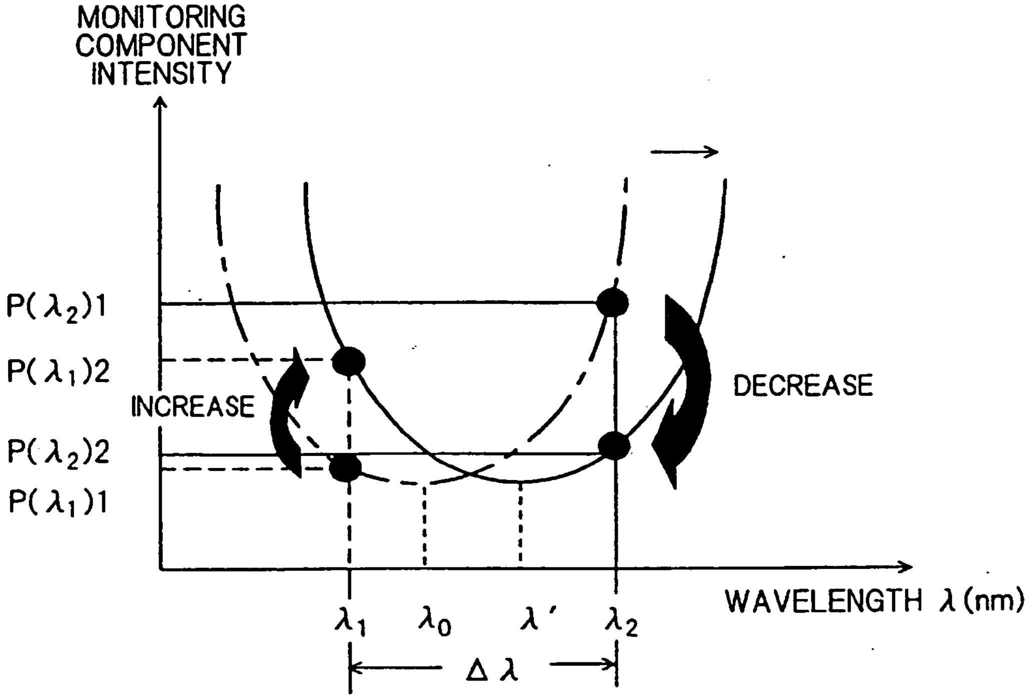


FIG.27B

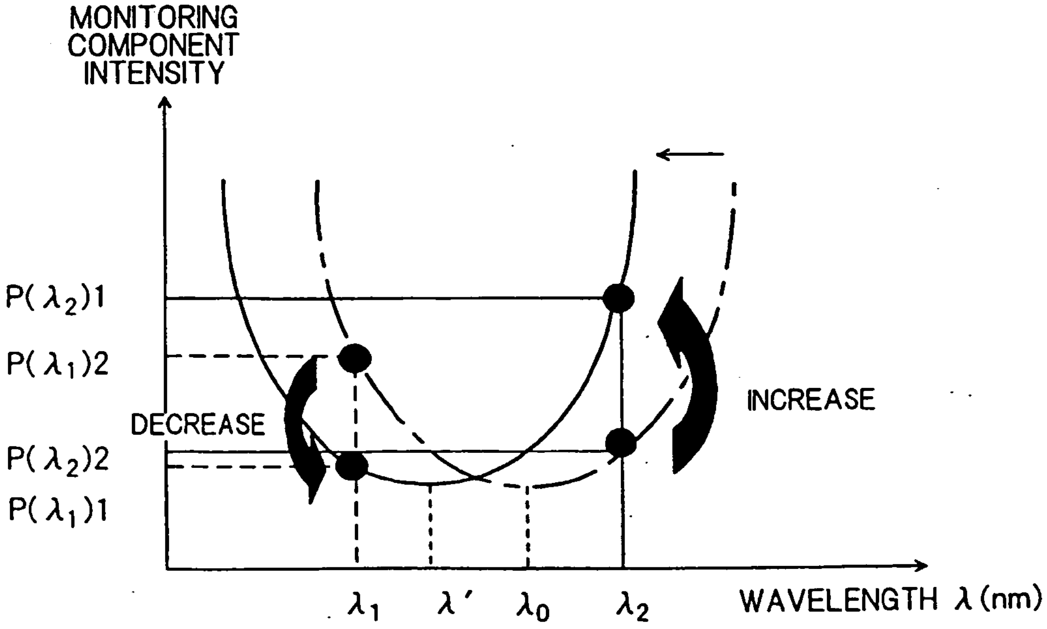


FIG.28

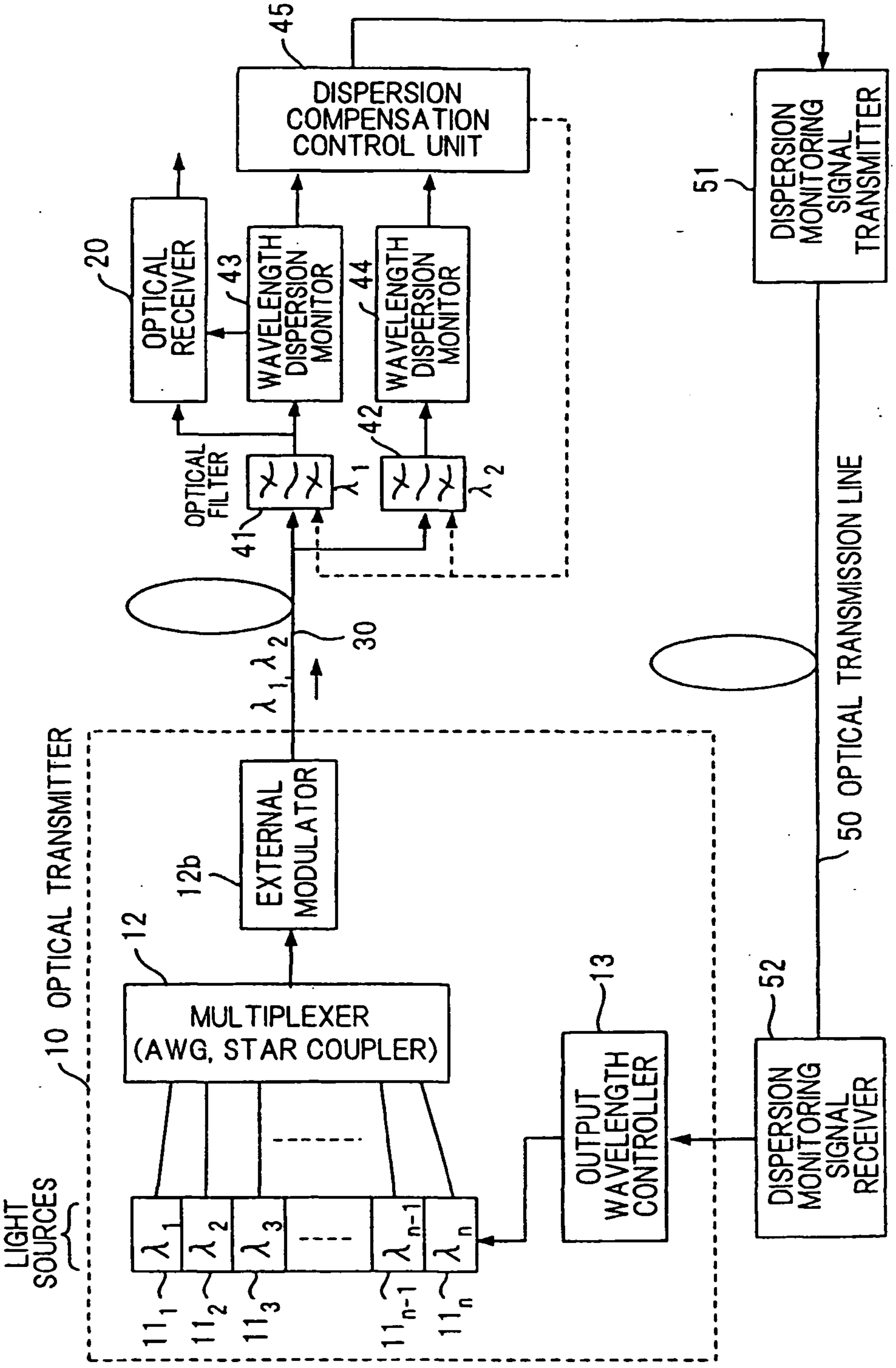

45
DISPERSION COMPENSATION CONTROL UNIT
20
OPTICAL RECEIVER
43
WAVELENGTH DISPERSION MONITOR
44
WAVELENGTH DISPERSION MONITOR
51
DISPERSION MONITORING SIGNAL TRANSMITTER
OPTICAL FILTER
41
42
λ1
λ2
30
λ1, λ2
50 OPTICAL TRANSMISSION LINE
10 OPTICAL TRANSMITTER
12
12b
EXTERNAL MODULATOR
MULTIPLEXER (AWG, STAR COUPLER)
13
OUTPUT WAVELENGTH CONTROLLER
52
DISPERSION MONITORING SIGNAL RECEIVER
LIGHT SOURCES
λ1
λ2
λ3
λn-1
λn
11_1
11_2
11_3
11_n-1
11_n

FIG. 29

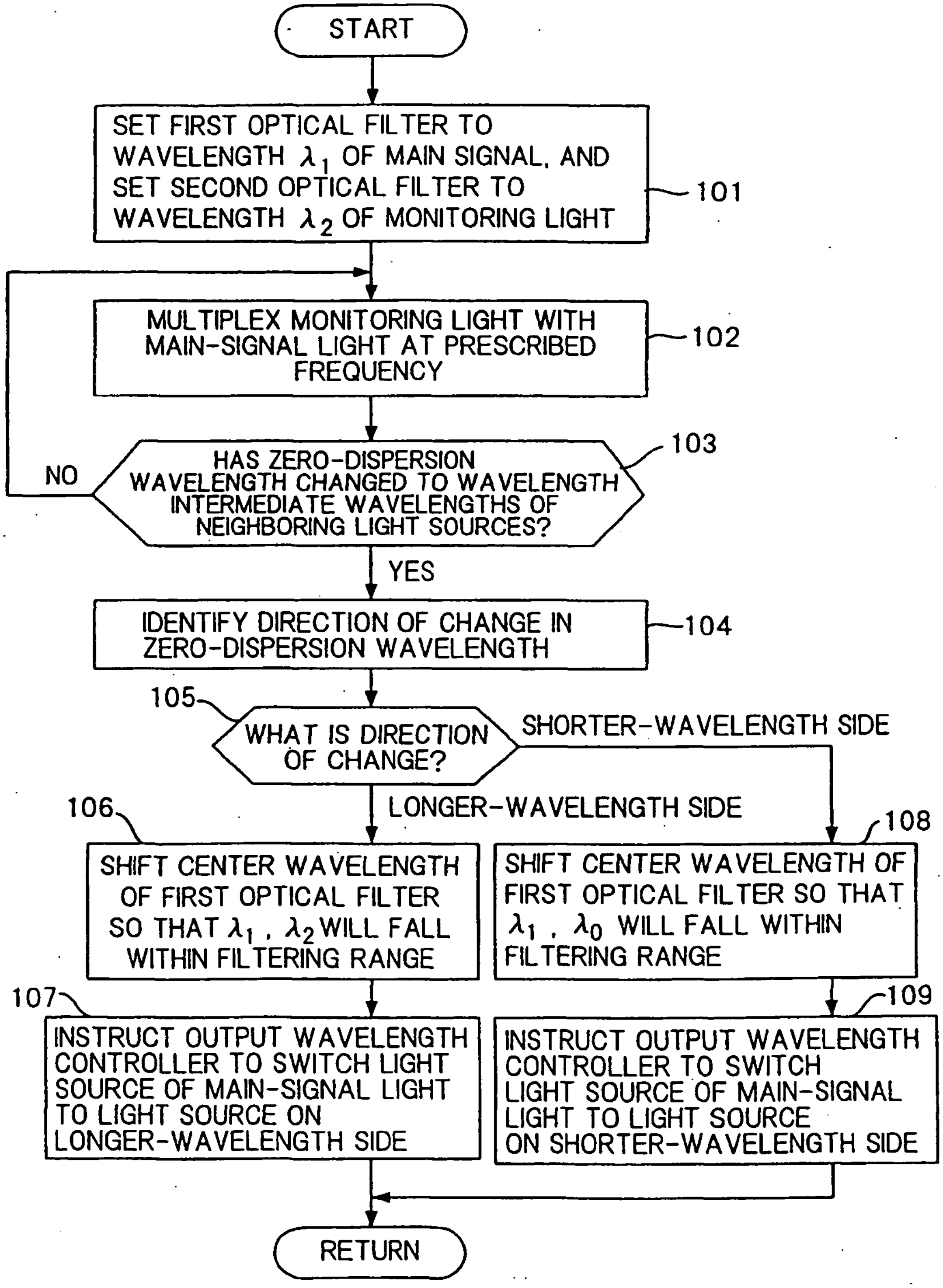

START
SET FIRST OPTICAL FILTER TO WAVELENGTH λ_1 OF MAIN SIGNAL, AND SET SECOND OPTICAL FILTER TO WAVELENGTH λ_2 OF MONITORING LIGHT
101
MULTIPLEX MONITORING LIGHT WITH MAIN-SIGNAL LIGHT AT PRESCRIBED FREQUENCY
102
HAS ZERO-DISPERSION WAVELENGTH CHANGED TO WAVELENGTH INTERMEDIATE WAVELENGTHS OF NEIGHBORING LIGHT SOURCES?
103
NO
YES
IDENTIFY DIRECTION OF CHANGE IN ZERO-DISPERSION WAVELENGTH
104
105
WHAT IS DIRECTION OF CHANGE?
SHORTER-WAVELENGTH SIDE
LONGER-WAVELENGTH SIDE
106
SHIFT CENTER WAVELENGTH OF FIRST OPTICAL FILTER SO THAT λ_1, λ_2 WILL FALL WITHIN FILTERING RANGE
108
SHIFT CENTER WAVELENGTH OF FIRST OPTICAL FILTER SO THAT λ_1, λ_0 WILL FALL WITHIN FILTERING RANGE
107
INSTRUCT OUTPUT WAVELENGTH CONTROLLER TO SWITCH LIGHT SOURCE OF MAIN-SIGNAL LIGHT TO LIGHT SOURCE ON LONGER-WAVELENGTH SIDE
109
INSTRUCT OUTPUT WAVELENGTH CONTROLLER TO SWITCH LIGHT SOURCE OF MAIN-SIGNAL LIGHT TO LIGHT SOURCE ON SHORTER-WAVELENGTH SIDE
RETURN

FIG.30

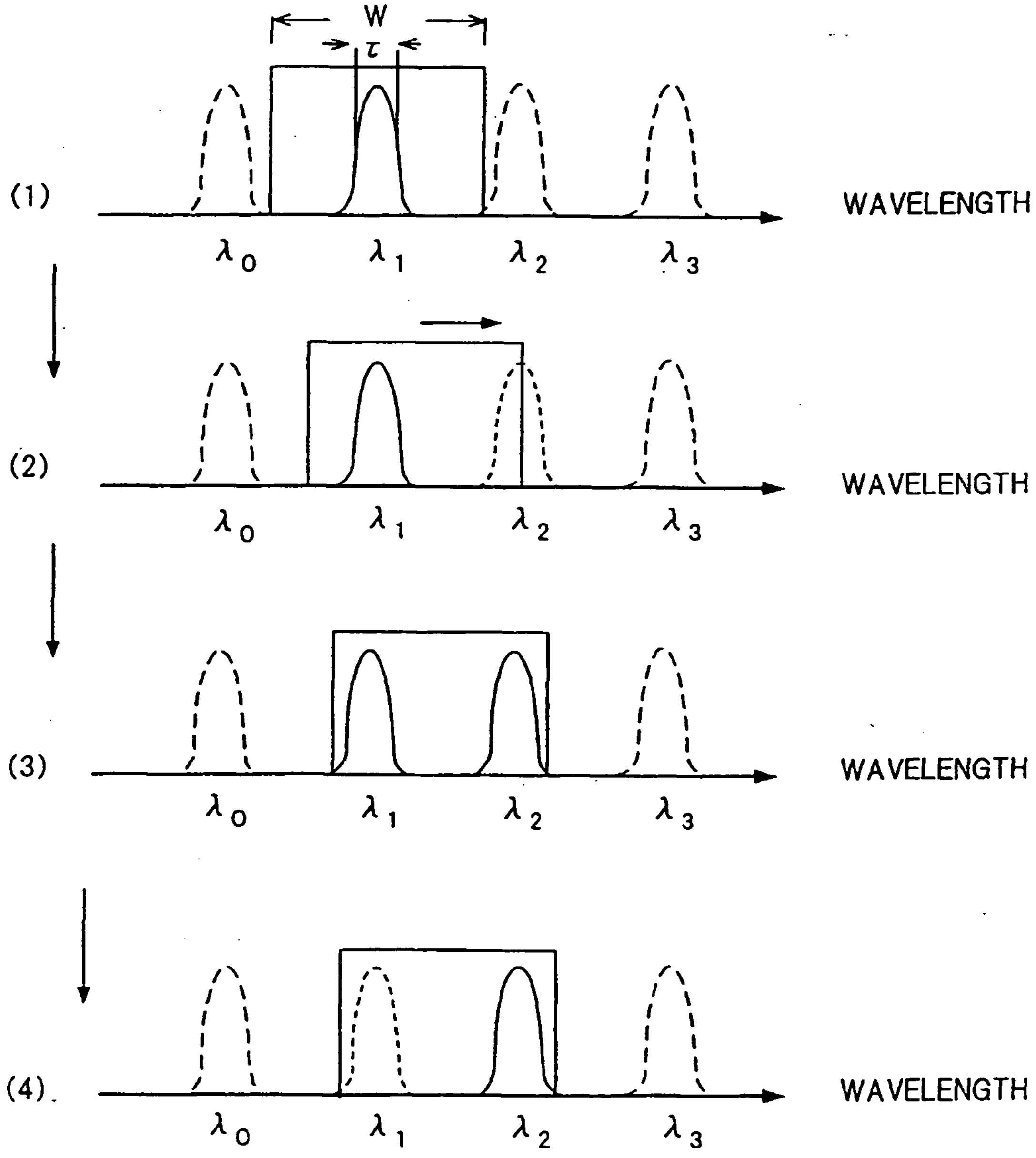

W
τ
(1)
WAVELENGTH
λ0
λ1
λ2
λ3
(2)
WAVELENGTH
λ0
λ1
λ2
λ3
(3)
WAVELENGTH
λ0
λ1
λ2
λ3
(4)
WAVELENGTH
λ0
λ1
λ2
λ3

FIG.31

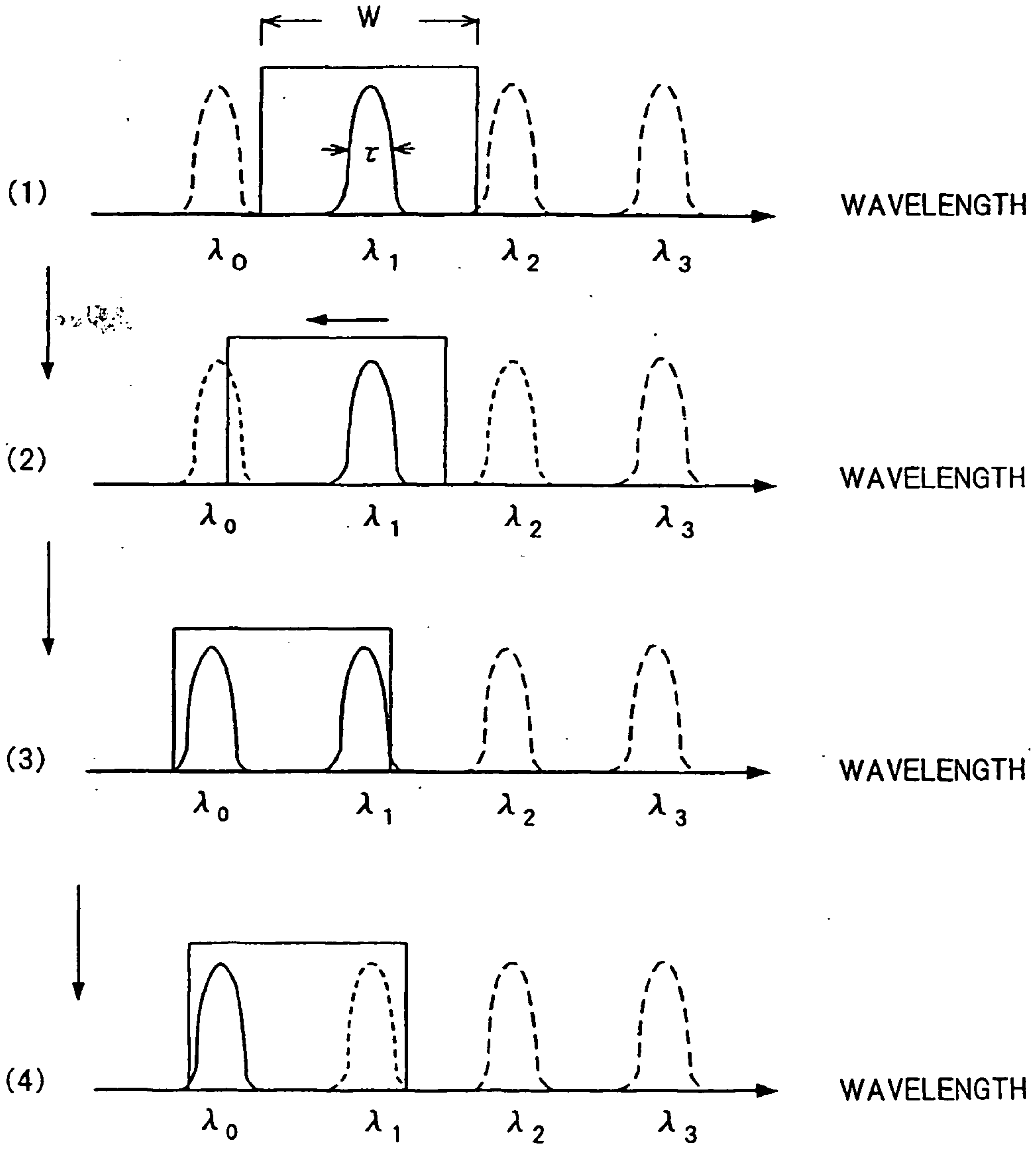

W
τ
(1)
WAVELENGTH
λ0
λ1
λ2
λ3
(2)
WAVELENGTH
λ0
λ1
λ2
λ3
(3)
WAVELENGTH
λ0
λ1
λ2
λ3
(4)
WAVELENGTH
λ0
λ1
λ2
λ3

FIG.32

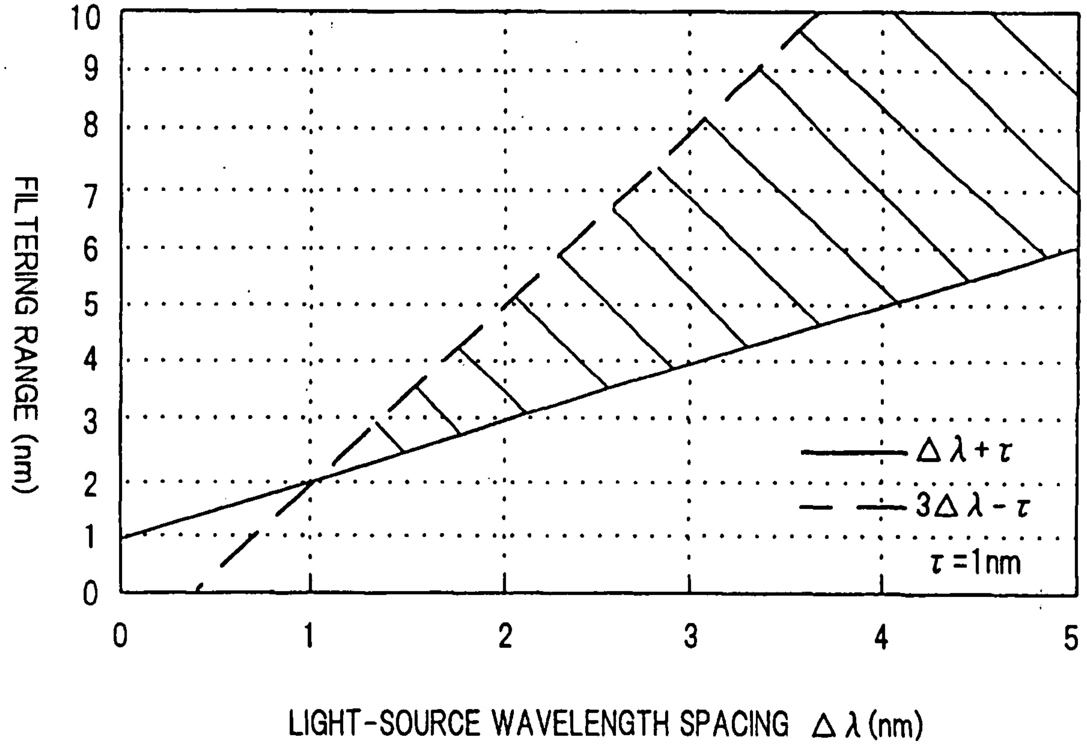

10
9
8
7
6
5
4
3
2
1
0
FILTERING RANGE (nm)
0
1
2
3
4
5
LIGHT-SOURCE WAVELENGTH SPACING $\Delta\lambda$ (nm)
$\Delta\lambda+\tau$
$3\Delta\lambda-\tau$
τ =1nm

FIG.33A

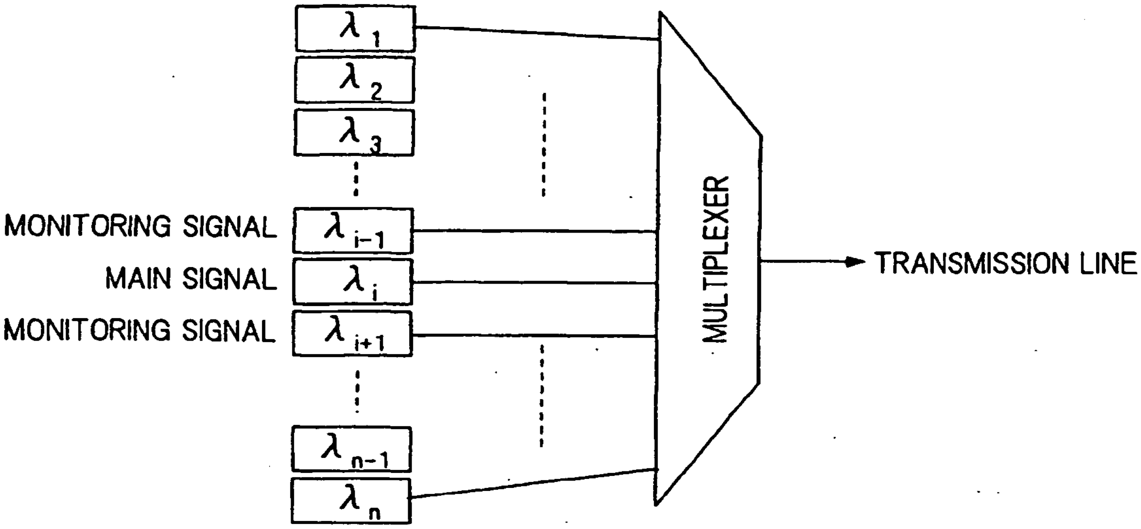

λ_1
λ_2
λ_3
MONITORING SIGNAL
λ_{i-1}
MAIN SIGNAL
λ_i
MONITORING SIGNAL
λ_{i+1}
λ_{n-1}
λ_n
MULTIPLEXER
TRANSMISSION LINE

FIG.33B

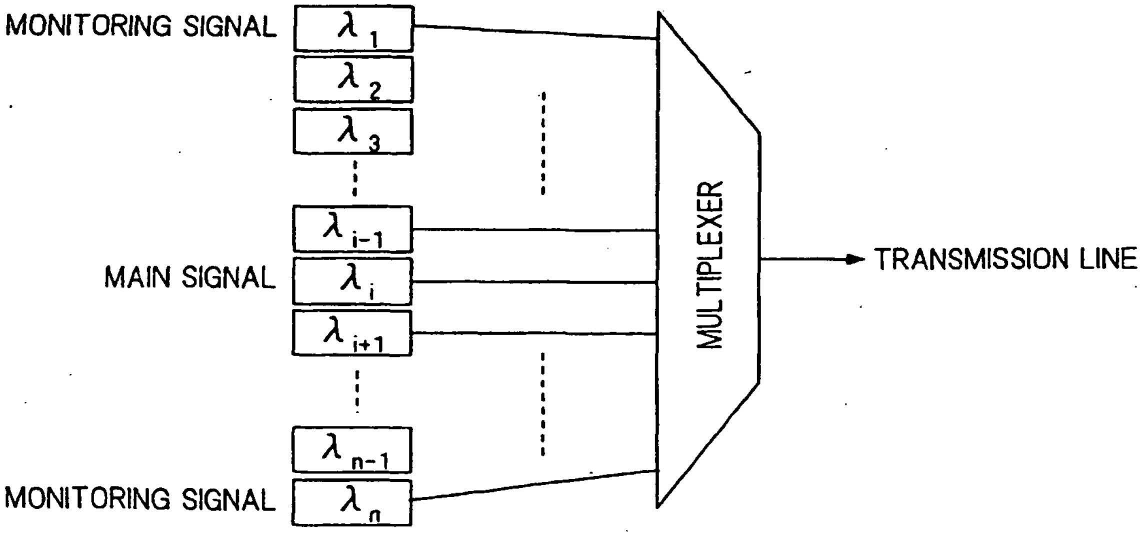

MONITORING SIGNAL
λ_1
λ_2
λ_3
λ_{i-1}
MAIN SIGNAL
λ_i
λ_{i+1}
λ_{n-1}
MONITORING SIGNAL
λ_n
MULTIPLEXER
TRANSMISSION LINE

FIG.34

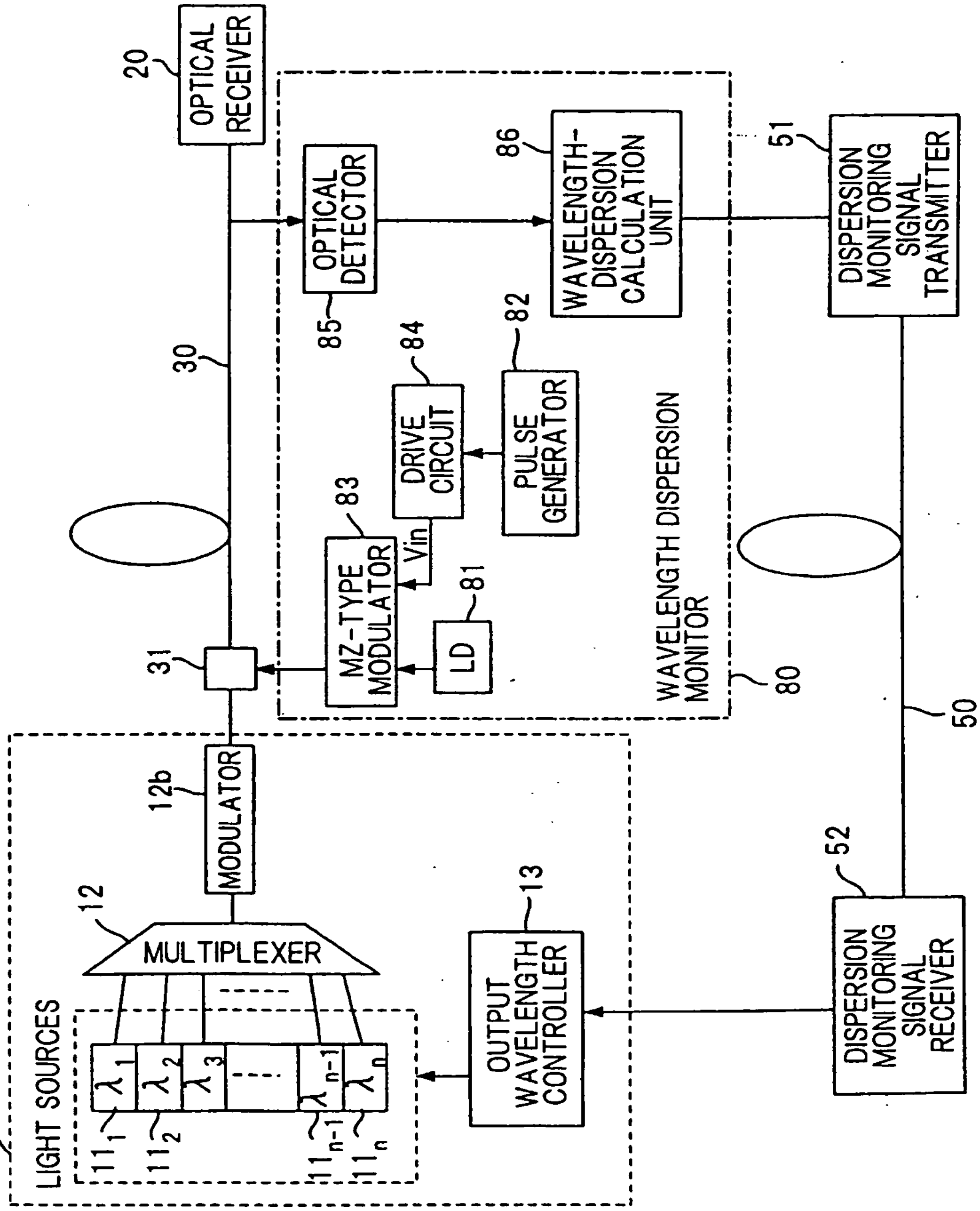

10 OPTICAL TRANSMITTER
LIGHT SOURCES
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
11_1
11_2
11_{n-1}
11_n
12
MULTIPLEXER
12b
MODULATOR
13
OUTPUT WAVELENGTH CONTROLLER
31
30
20
OPTICAL RECEIVER
80
WAVELENGTH DISPERSION MONITOR
81
LD
83
MZ-TYPE MODULATOR
Vin
84
DRIVE CIRCUIT
82
PULSE GENERATOR
85
OPTICAL DETECTOR
86
WAVELENGTH-DISPERSION CALCULATION UNIT
51
DISPERSION MONITORING SIGNAL TRANSMITTER
50
52
DISPERSION MONITORING SIGNAL RECEIVER

FIG.35A

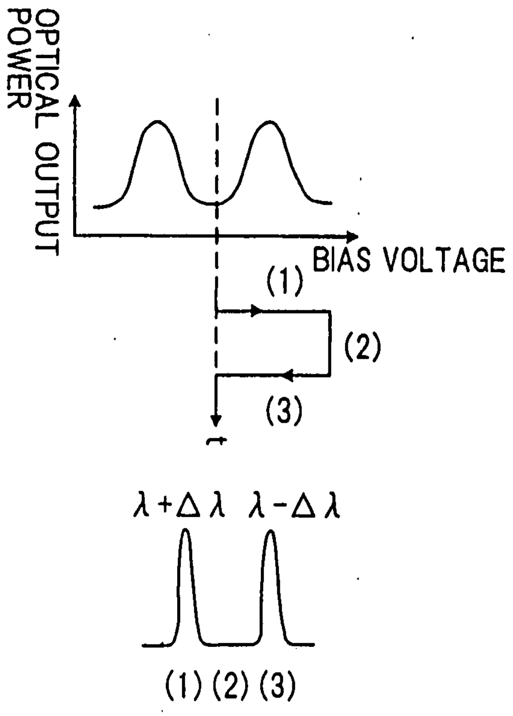

OPTICAL OUTPUT POWER
BIAS VOLTAGE
(1)
(2)
(3)
t
λ+Δλ
λ-Δλ
(1) (2) (3)

FIG.35B

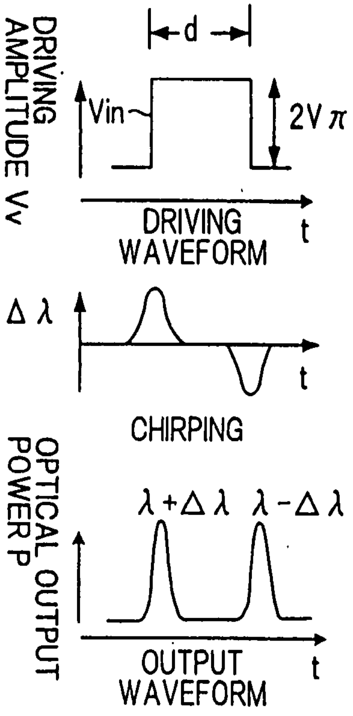

DRIVING AMPLITUDE Vv
Vin
d
2Vπ
DRIVING WAVEFORM
t
Δλ
t
CHIRPING
OPTICAL OUTPUT POWER P
λ+Δλ
λ-Δλ
OUTPUT WAVEFORM
t

FIG.35C

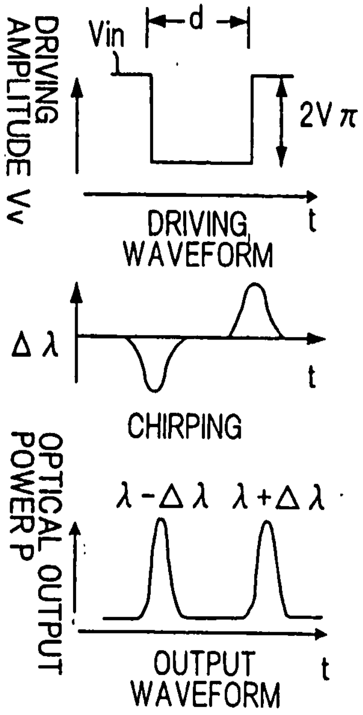

DRIVING AMPLITUDE Vv
Vin
d
2Vπ
DRIVING WAVEFORM
t
Δλ
t
CHIRPING
OPTICAL OUTPUT POWER P
λ-Δλ
λ+Δλ
OUTPUT WAVEFORM
t

FIG.36

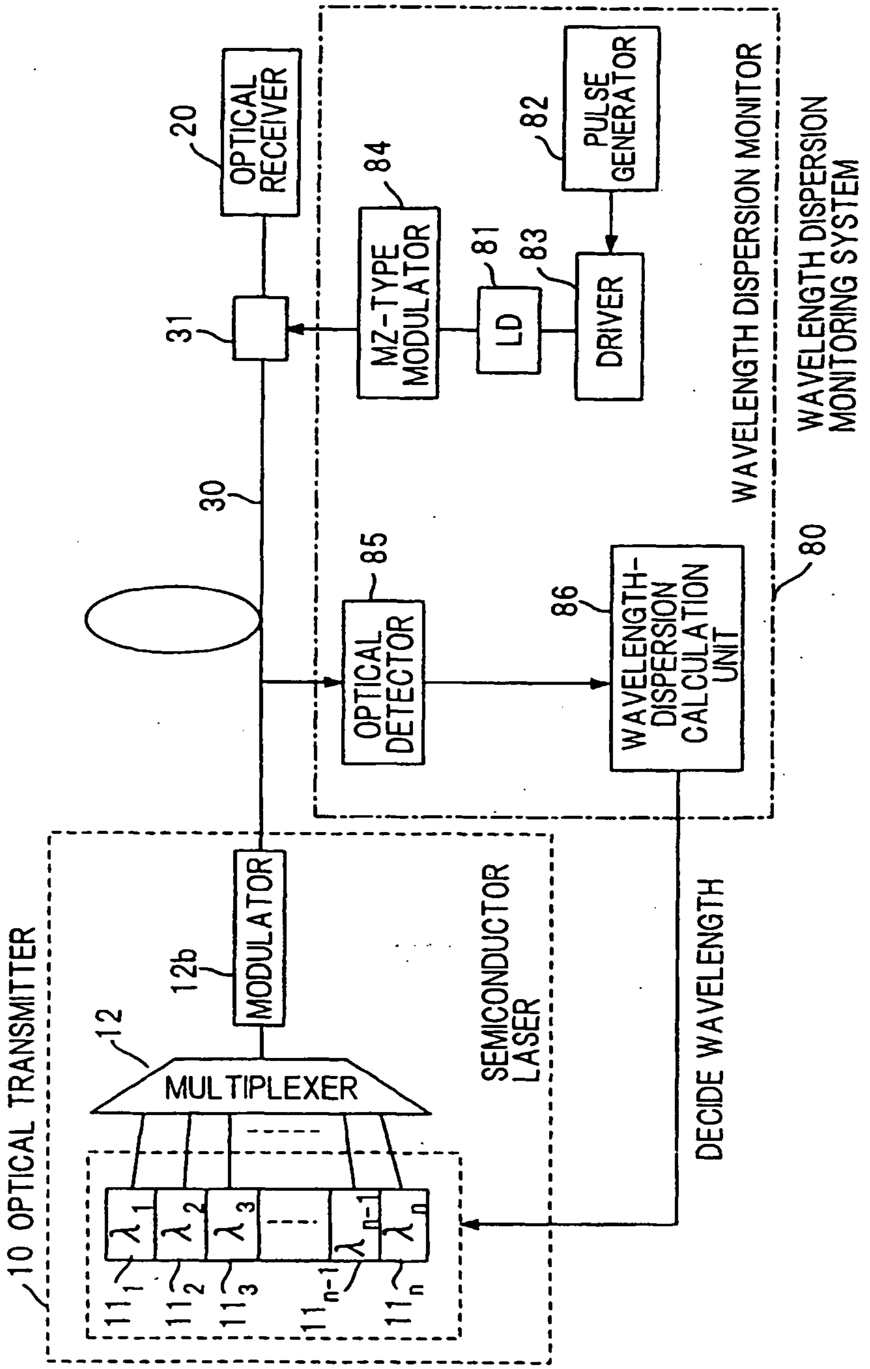

10 OPTICAL TRANSMITTER
SEMICONDUCTOR LASER
11_1
11_2
11_3
11_{n-1}
11_n
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
12
MULTIPLEXER
12b
MODULATOR
30
31
20
OPTICAL RECEIVER
84
MZ-TYPE MODULATOR
81
LD
83
DRIVER
82
PULSE GENERATOR
85
OPTICAL DETECTOR
86
WAVELENGTH-DISPERSION CALCULATION UNIT
WAVELENGTH DISPERSION MONITOR
80
WAVELENGTH DISPERSION MONITORING SYSTEM
DECIDE WAVELENGTH

FIG.37

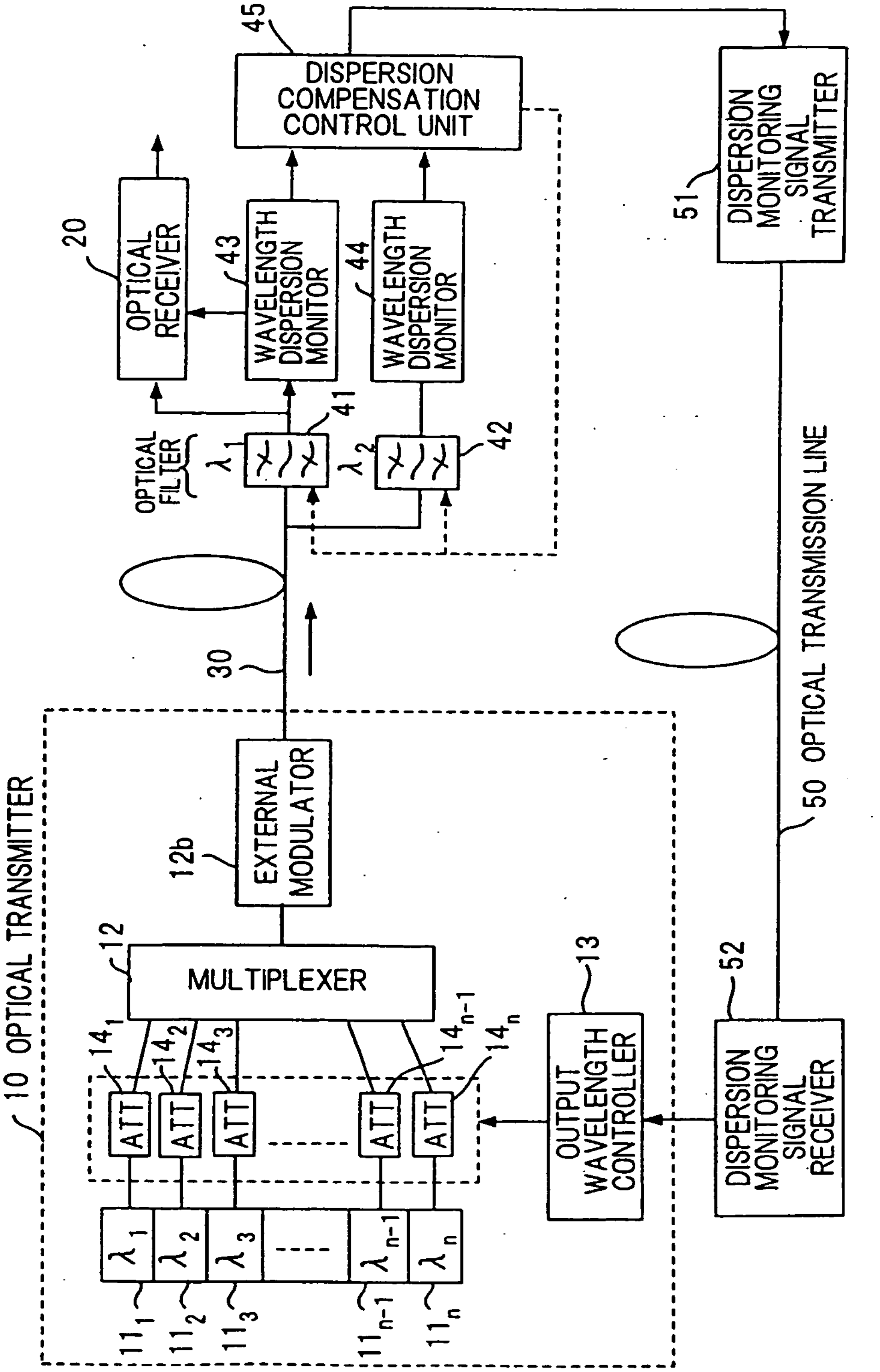

10 OPTICAL TRANSMITTER
11_1
11_2
11_3
11_{n-1}
11_n
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
ATT
14_1
14_2
14_3
14_{n-1}
14_n
12
MULTIPLEXER
12b
EXTERNAL MODULATOR
13
OUTPUT WAVELENGTH CONTROLLER
30
OPTICAL FILTER
λ_1
41
λ_2
42
20
OPTICAL RECEIVER
43
WAVELENGTH DISPERSION MONITOR
44
WAVELENGTH DISPERSION MONITOR
45
DISPERSION COMPENSATION CONTROL UNIT
51
DISPERSION MONITORING SIGNAL TRANSMITTER
50 OPTICAL TRANSMISSION LINE
52
DISPERSION MONITORING SIGNAL RECEIVER

FIG.38

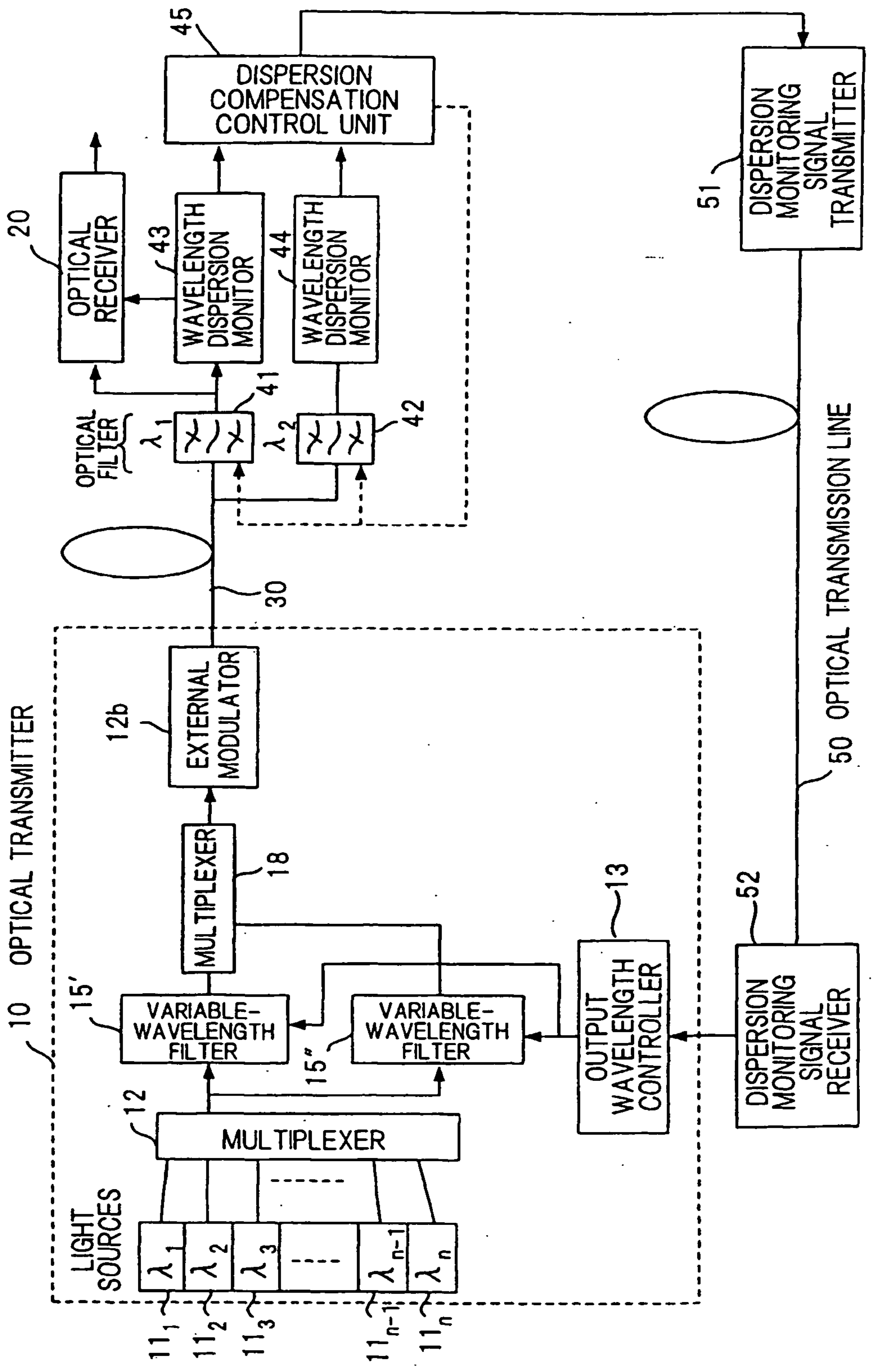

10 OPTICAL TRANSMITTER
LIGHT SOURCES
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
11_1
11_2
11_3
11_{n-1}
11_n
12
MULTIPLEXER
15'
VARIABLE-WAVELENGTH FILTER
15"
VARIABLE-WAVELENGTH FILTER
13
OUTPUT WAVELENGTH CONTROLLER
18
MULTIPLEXER
12b
EXTERNAL MODULATOR
30
OPTICAL FILTER
λ_1
41
λ_2
42
43
WAVELENGTH DISPERSION MONITOR
44
WAVELENGTH DISPERSION MONITOR
20
OPTICAL RECEIVER
45
DISPERSION COMPENSATION CONTROL UNIT
51
DISPERSION MONITORING SIGNAL TRANSMITTER
50 OPTICAL TRANSMISSION LINE
52
DISPERSION MONITORING SIGNAL RECEIVER

FIG.39

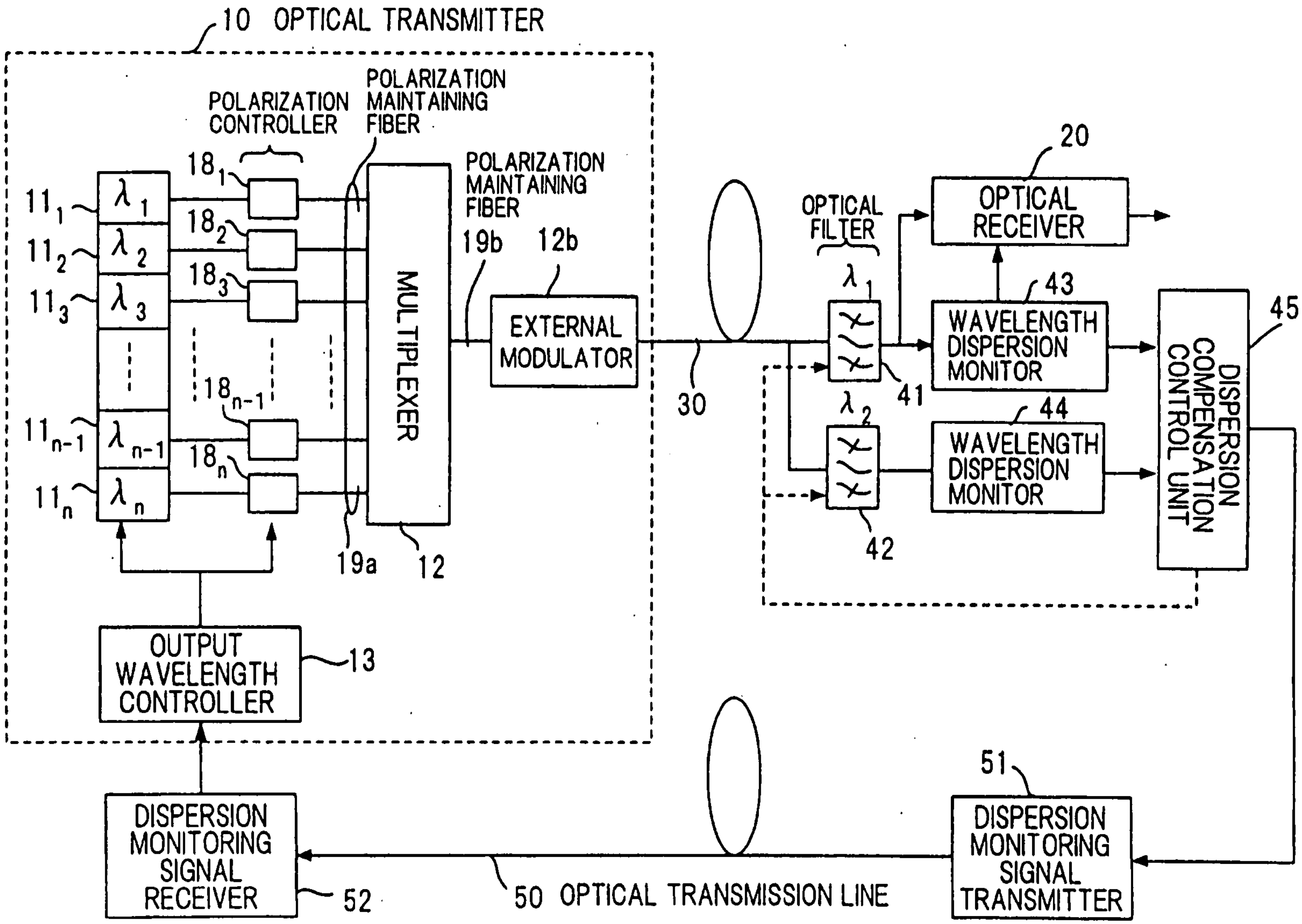

10 OPTICAL TRANSMITTER
POLARIZATION CONTROLLER
POLARIZATION MAINTAINING FIBER
POLARIZATION MAINTAINING FIBER
11_1
11_2
11_3
11_{n-1}
11_n
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
18_1
18_2
18_3
18_{n-1}
18_n
MULTIPLEXER
19a
12
19b
12b
EXTERNAL MODULATOR
OUTPUT WAVELENGTH CONTROLLER
13
30
OPTICAL FILTER
λ_1
λ_2
41
42
20
OPTICAL RECEIVER
43
WAVELENGTH DISPERSION MONITOR
44
WAVELENGTH DISPERSION MONITOR
45
DISPERSION COMPENSATION CONTROL UNIT
51
DISPERSION MONITORING SIGNAL TRANSMITTER
50 OPTICAL TRANSMISSION LINE
DISPERSION MONITORING SIGNAL RECEIVER
52

FIG.40A

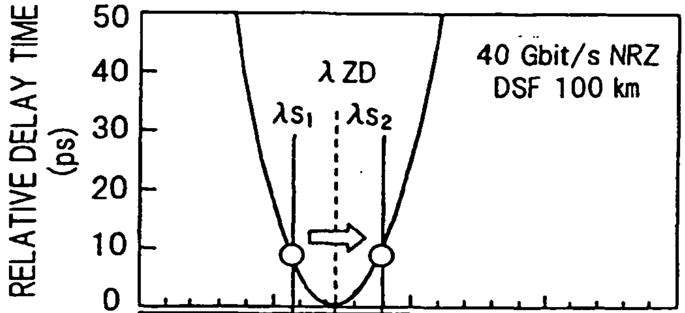


FIG.40B

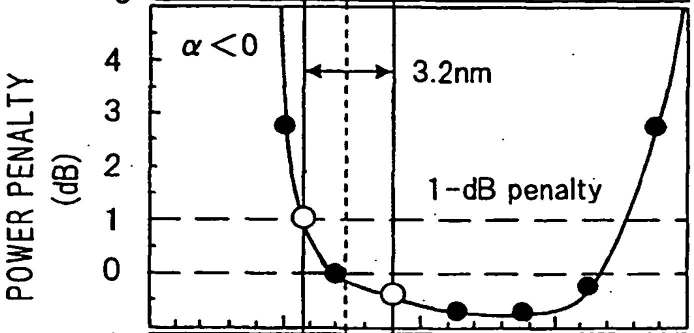


FIG.40C

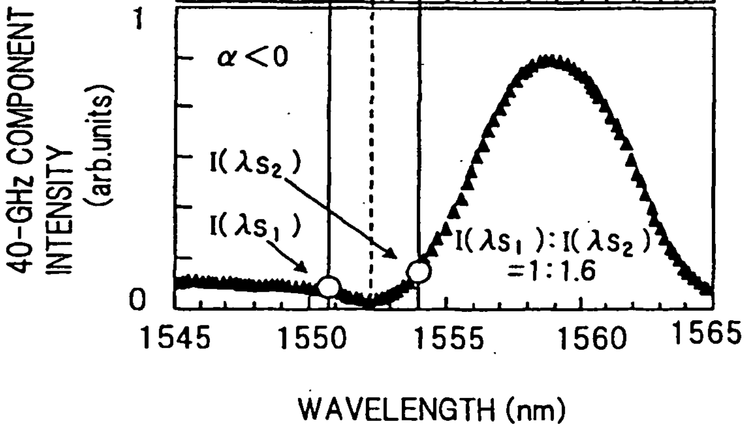


FIG.41

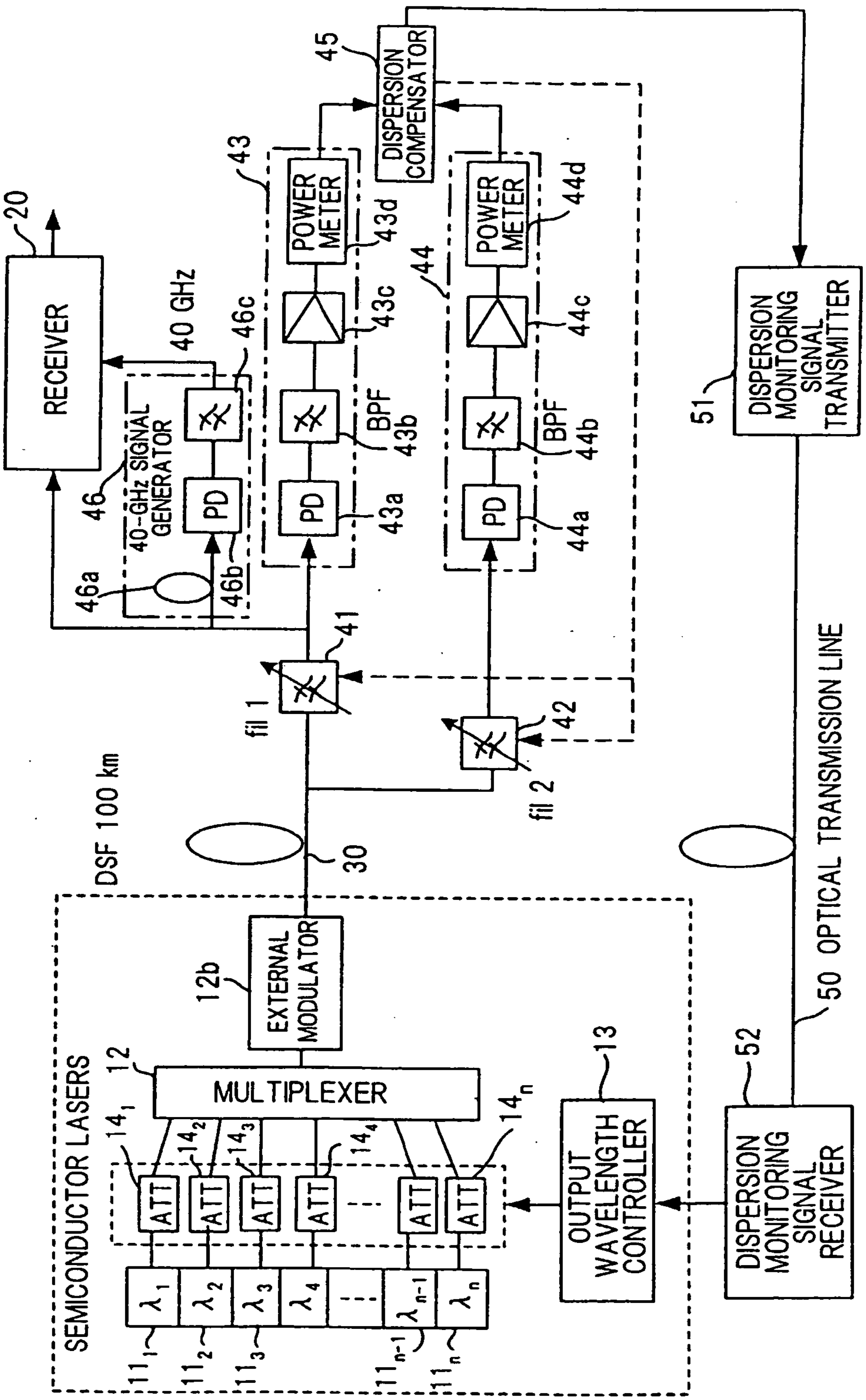

RECEIVER
20
40 GHz
46c
40-GHz SIGNAL GENERATOR
46
PD
46a
46b
43
POWER METER
43d
43c
BPF
43b
PD
43a
41
fil 1
45
DISPERSION COMPENSATOR
44
POWER METER
44d
44c
BPF
44b
PD
44a
42
fil 2
DSF 100 km
30
DISPERSION MONITORING SIGNAL TRANSMITTER
51
50 OPTICAL TRANSMISSION LINE
SEMICONDUCTOR LASERS
EXTERNAL MODULATOR
12b
12
MULTIPLEXER
13
OUTPUT WAVELENGTH CONTROLLER
52
DISPERSION MONITORING SIGNAL RECEIVER
ATT
14_1
14_2
14_3
14_4
14_n
λ_1
λ_2
λ_3
λ_4
λ_{n-1}
λ_n
11_1
11_2
11_3
11_{n-1}
11_n

FIG.42

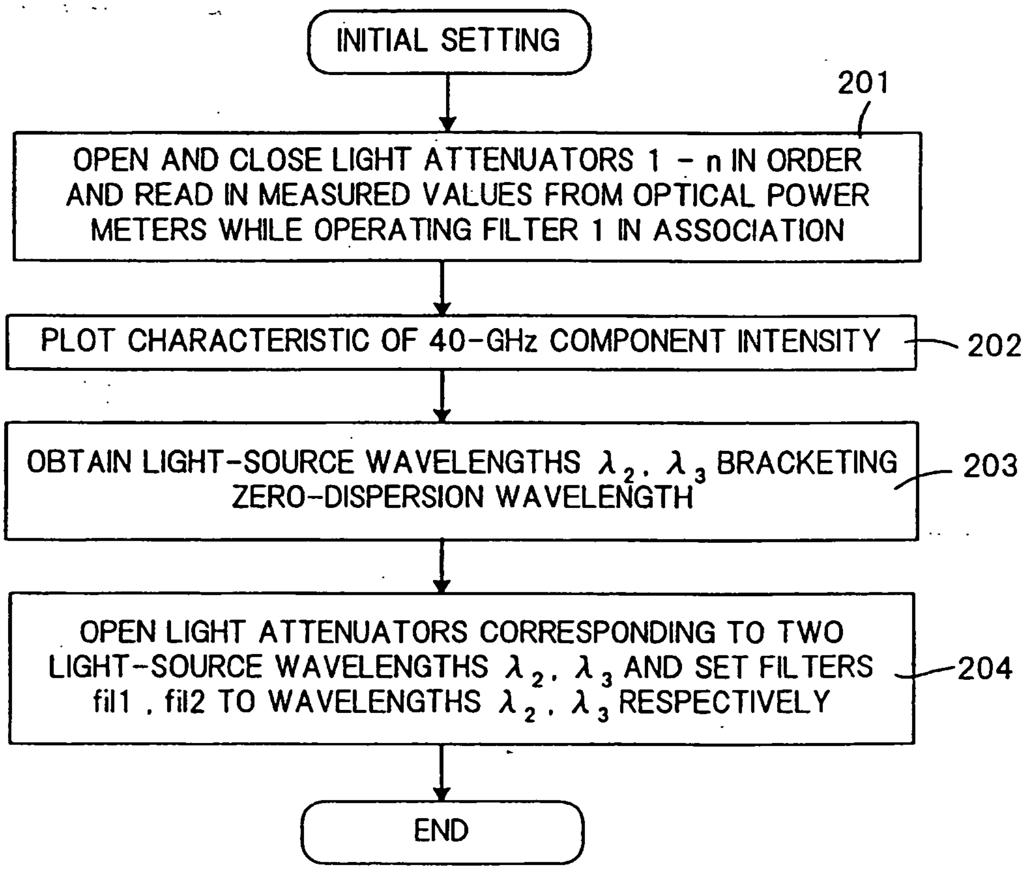

INITIAL SETTING
201
OPEN AND CLOSE LIGHT ATTENUATORS 1 - n IN ORDER AND READ IN MEASURED VALUES FROM OPTICAL POWER METERS WHILE OPERATING FILTER 1 IN ASSOCIATION
PLOT CHARACTERISTIC OF 40-GHz COMPONENT INTENSITY
202
OBTAIN LIGHT-SOURCE WAVELENGTHS λ_2, λ_3 BRACKETING ZERO-DISPERSION WAVELENGTH
203
OPEN LIGHT ATTENUATORS CORRESPONDING TO TWO LIGHT-SOURCE WAVELENGTHS λ_2, λ_3 AND SET FILTERS fil1 , fil2 TO WAVELENGTHS λ_2, λ_3 RESPECTIVELY
204
END

FIG. 43A

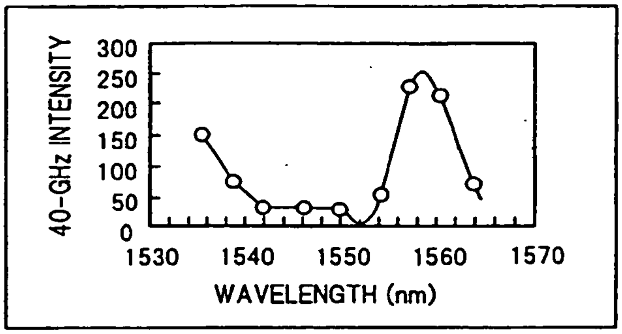


FIG. 43B

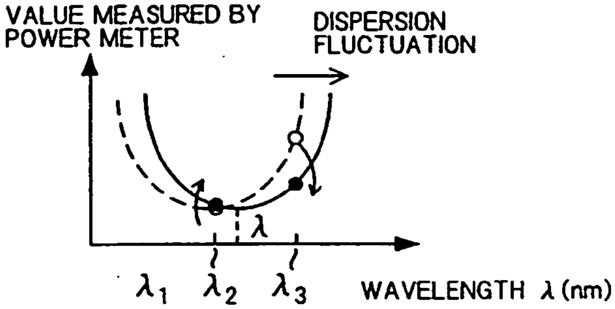

VALUE MEASURED BY POWER METER
DISPERSION FLUCTUATION
λ
λ1
λ2
λ3
WAVELENGTH λ (nm)

FIG. 43C

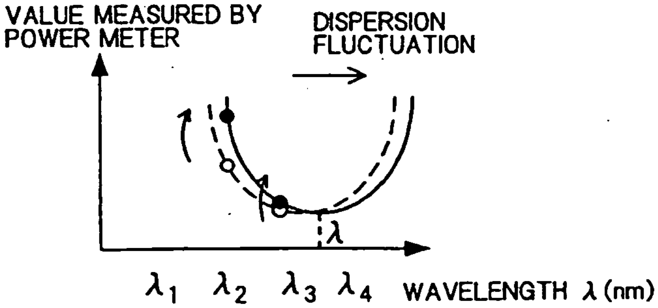

VALUE MEASURED BY POWER METER
DISPERSION FLUCTUATION
λ
λ1
λ2
λ3
λ4
WAVELENGTH λ (nm)

FIG. 43D

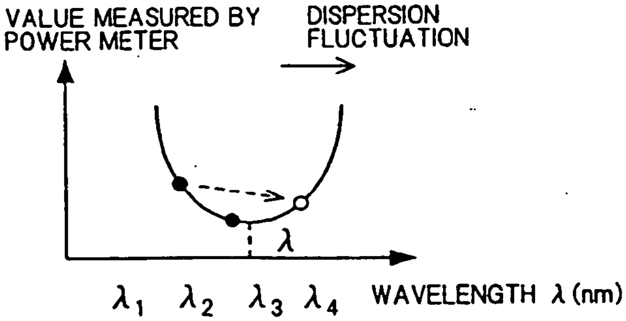

VALUE MEASURED BY POWER METER
DISPERSION FLUCTUATION
λ
λ1
λ2
λ3
λ4
WAVELENGTH λ (nm)

FIG.44

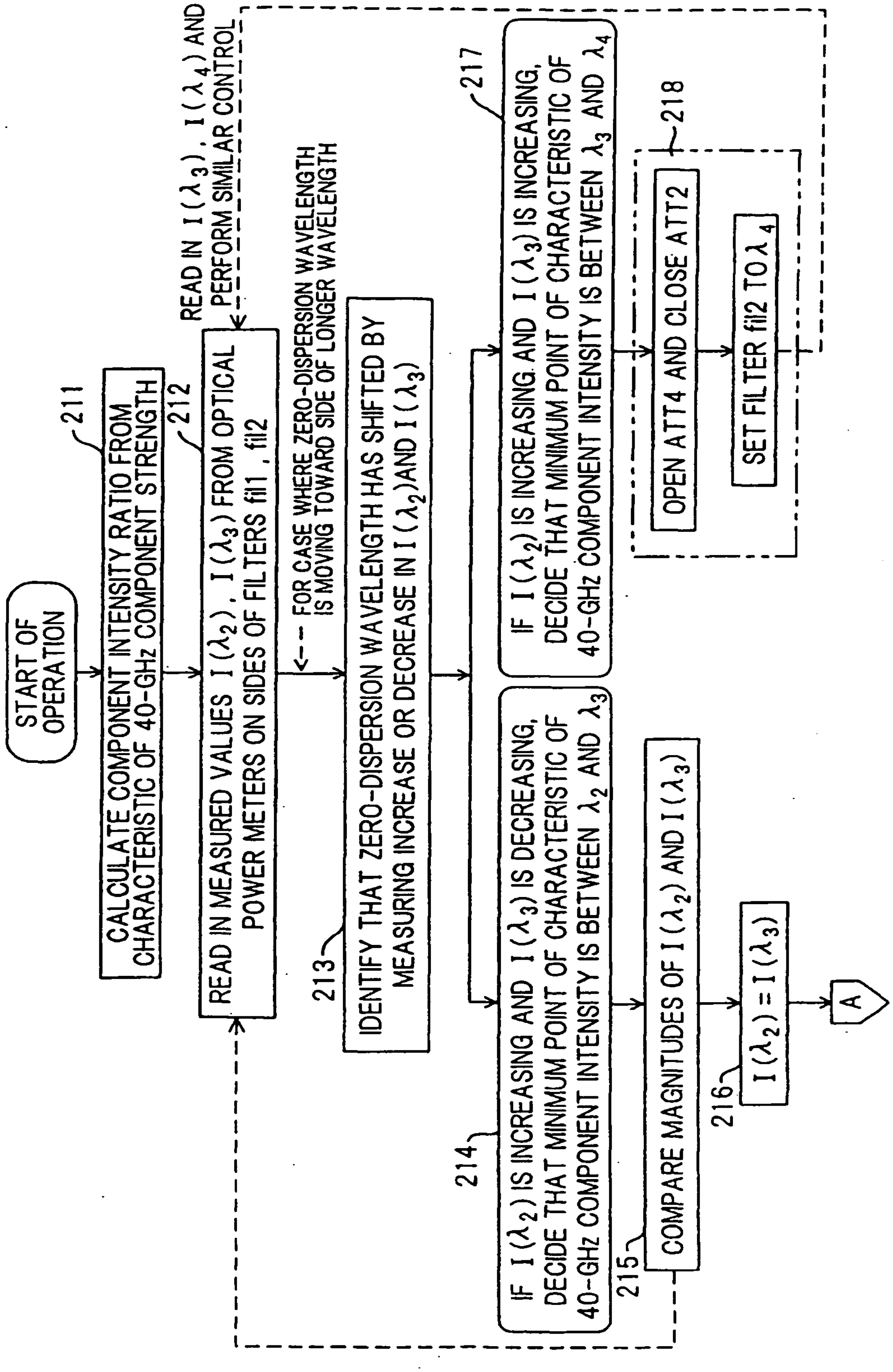

START OF OPERATION
211
CALCULATE COMPONENT INTENSITY RATIO FROM CHARACTERISTIC OF 40-GHz COMPONENT STRENGTH
212
READ IN MEASURED VALUES I(λ2), I(λ3) FROM OPTICAL POWER METERS ON SIDES OF FILTERS fil1, fil2
READ IN I(λ3), I(λ4) AND PERFORM SIMILAR CONTROL
FOR CASE WHERE ZERO-DISPERSION WAVELENGTH IS MOVING TOWARD SIDE OF LONGER WAVELENGTH
213
IDENTIFY THAT ZERO-DISPERSION WAVELENGTH HAS SHIFTED BY MEASURING INCREASE OR DECREASE IN I(λ2) AND I(λ3)
214
IF I(λ2) IS INCREASING AND I(λ3) IS DECREASING, DECIDE THAT MINIMUM POINT OF CHARACTERISTIC OF 40-GHz COMPONENT INTENSITY IS BETWEEN λ2 AND λ3
217
IF I(λ2) IS INCREASING AND I(λ3) IS INCREASING, DECIDE THAT MINIMUM POINT OF CHARACTERISTIC OF 40-GHz COMPONENT INTENSITY IS BETWEEN λ3 AND λ4
215
COMPARE MAGNITUDES OF I(λ2) AND I(λ3)
216
I(λ2) = I(λ3)
A
218
OPEN ATT4 AND CLOSE ATT2
SET FILTER fil2 TO λ4

FIG.45

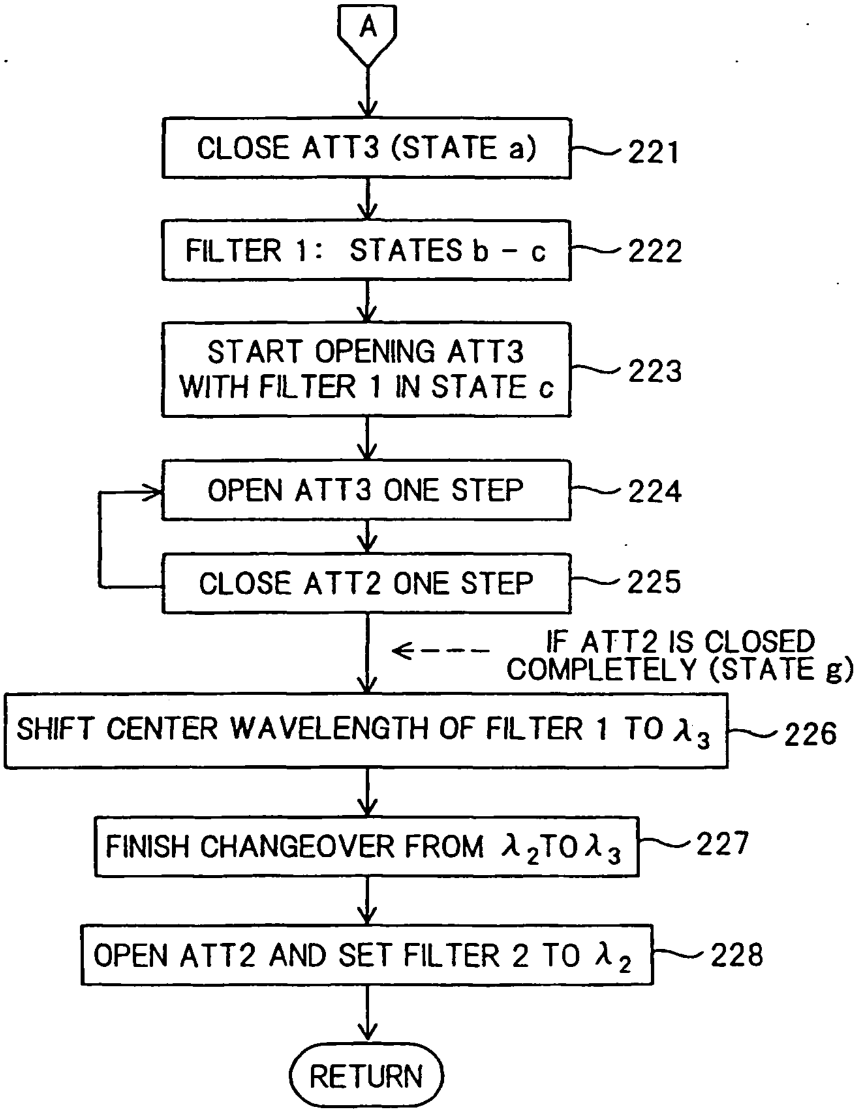

A
CLOSE ATT3 (STATE a)
221
FILTER 1: STATES b - c
222
START OPENING ATT3 WITH FILTER 1 IN STATE c
223
OPEN ATT3 ONE STEP
224
CLOSE ATT2 ONE STEP
225
IF ATT2 IS CLOSED COMPLETELY (STATE g)
SHIFT CENTER WAVELENGTH OF FILTER 1 TO λ_3
226
FINISH CHANGEOVER FROM λ_2 TO λ_3
227
OPEN ATT2 AND SET FILTER 2 TO λ_2
228
RETURN

FIG. 46

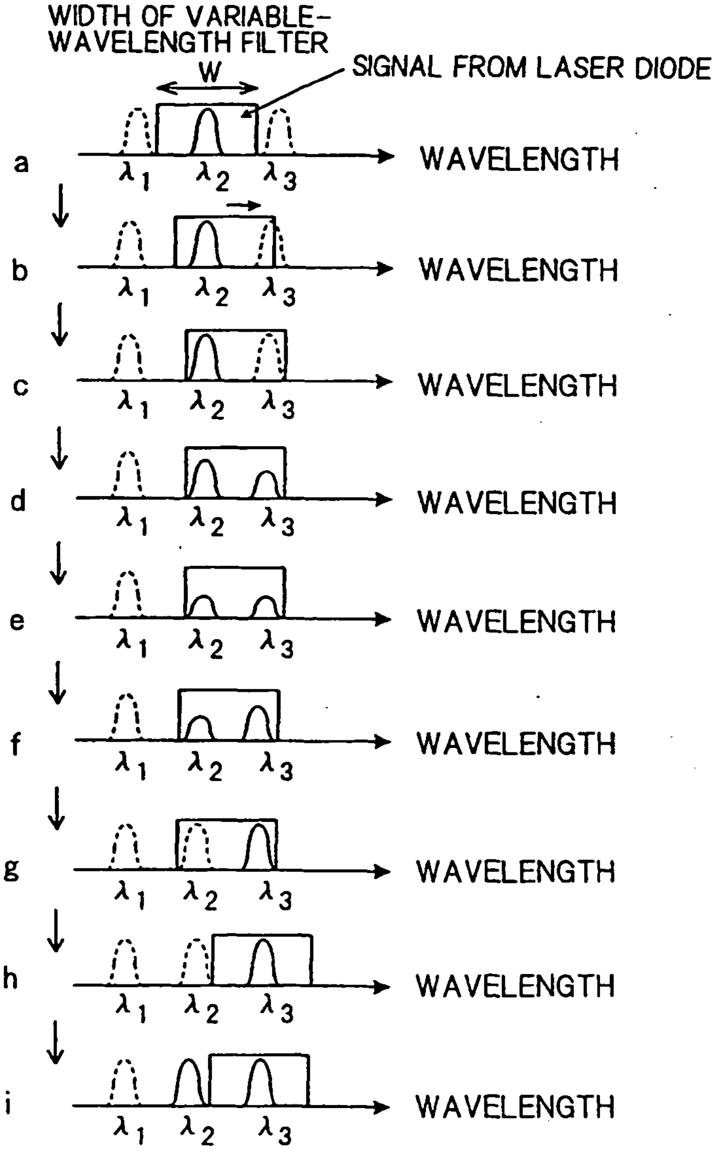

WIDTH OF VARIABLE-WAVELENGTH FILTER
W
SIGNAL FROM LASER DIODE
a
b
c
d
e
f
g
h
i
λ1
λ2
λ3
WAVELENGTH

FIG.47A

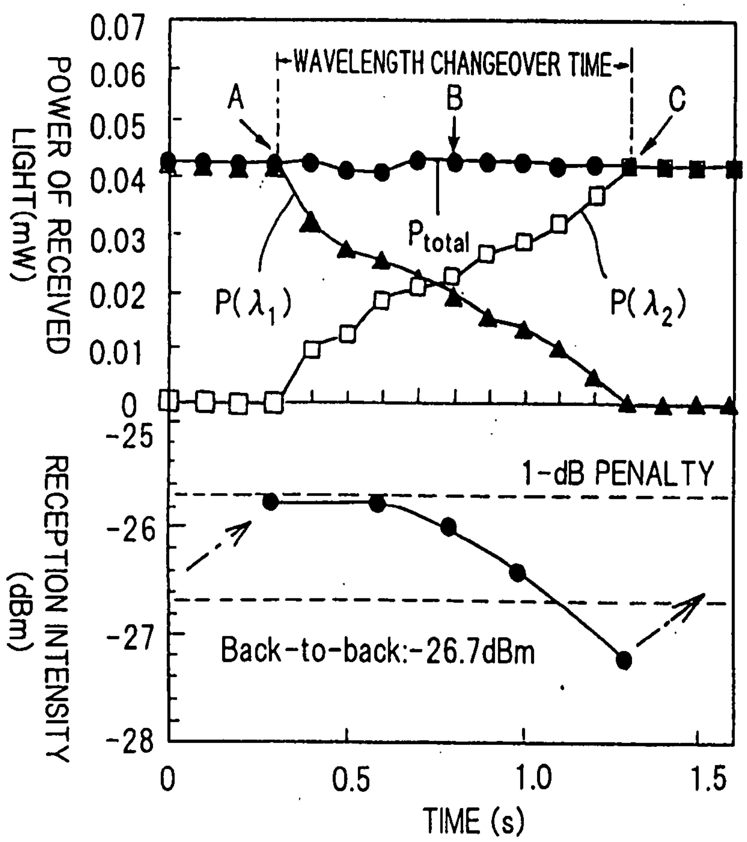


FIG.47B

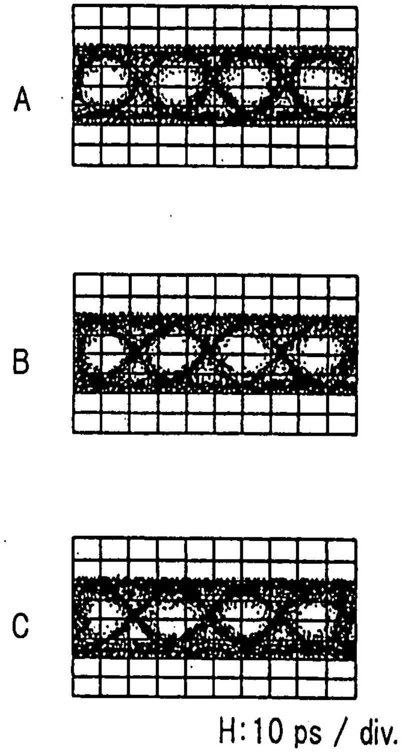


FIG.47C

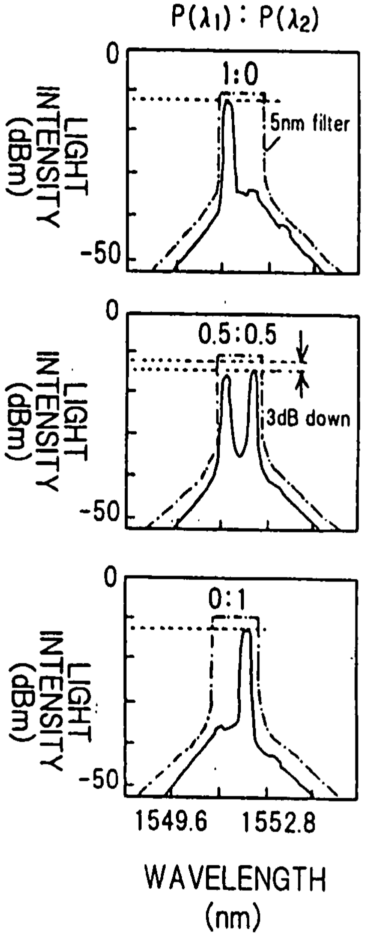


FIG.48

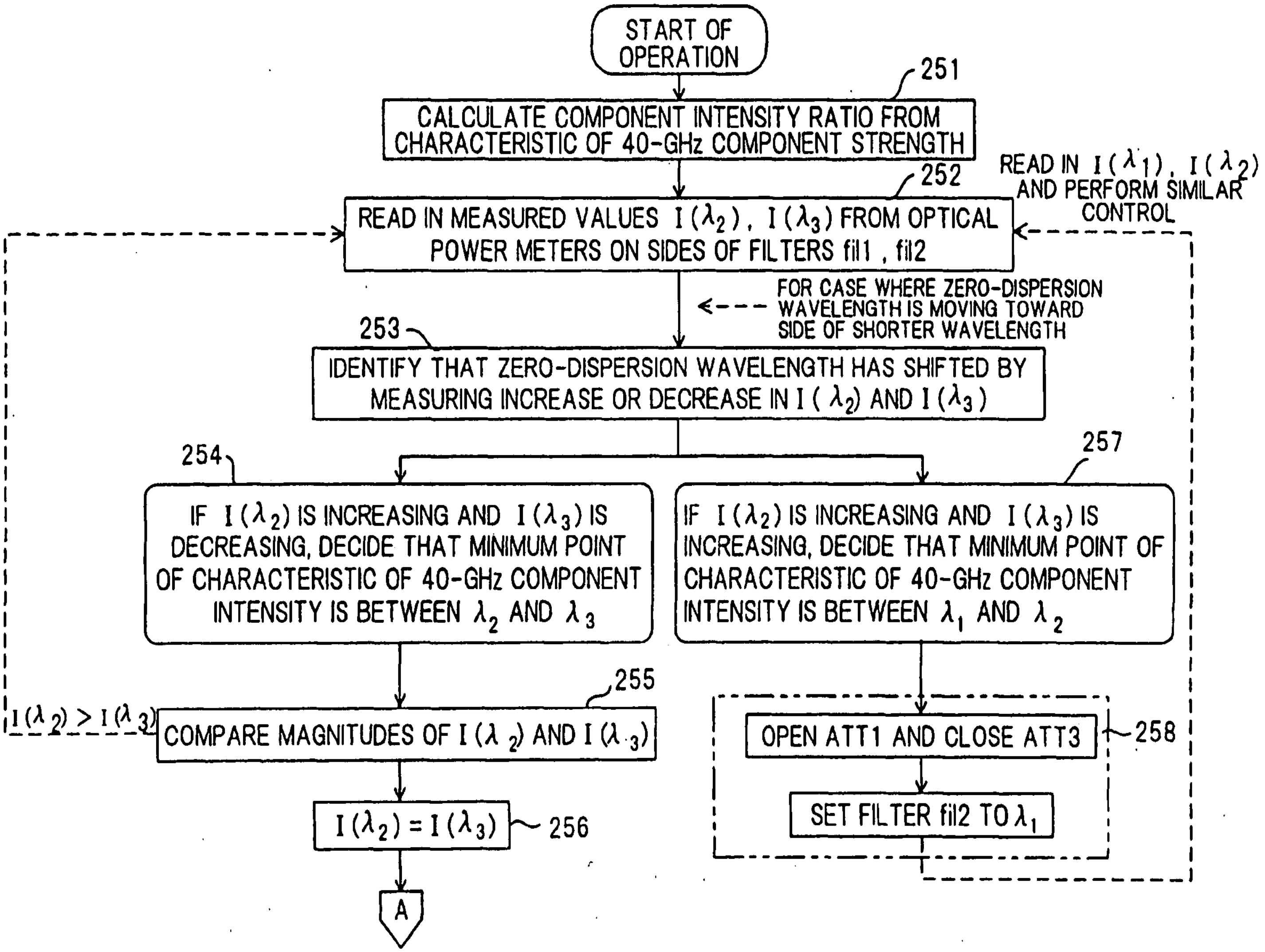

START OF OPERATION
251
CALCULATE COMPONENT INTENSITY RATIO FROM CHARACTERISTIC OF 40-GHz COMPONENT STRENGTH
252
READ IN MEASURED VALUES $I(\lambda_2)$, $I(\lambda_3)$ FROM OPTICAL POWER METERS ON SIDES OF FILTERS fil1 , fil2
READ IN $I(\lambda_1)$, $I(\lambda_2)$ AND PERFORM SIMILAR CONTROL
FOR CASE WHERE ZERO-DISPERSION WAVELENGTH IS MOVING TOWARD SIDE OF SHORTER WAVELENGTH
253
IDENTIFY THAT ZERO-DISPERSION WAVELENGTH HAS SHIFTED BY MEASURING INCREASE OR DECREASE IN $I(\lambda_2)$ AND $I(\lambda_3)$
254
IF $I(\lambda_2)$ IS INCREASING AND $I(\lambda_3)$ IS DECREASING, DECIDE THAT MINIMUM POINT OF CHARACTERISTIC OF 40-GHz COMPONENT INTENSITY IS BETWEEN λ_2 AND λ_3
257
IF $I(\lambda_2)$ IS INCREASING AND $I(\lambda_3)$ IS INCREASING, DECIDE THAT MINIMUM POINT OF CHARACTERISTIC OF 40-GHz COMPONENT INTENSITY IS BETWEEN λ_1 AND λ_2
255
$I(\lambda_2) > I(\lambda_3)$
COMPARE MAGNITUDES OF $I(\lambda_2)$ AND $I(\lambda_3)$
$I(\lambda_2) = I(\lambda_3)$
256
A
OPEN ATT1 AND CLOSE ATT3
258
SET FILTER fil2 TO λ_1

FIG.49A

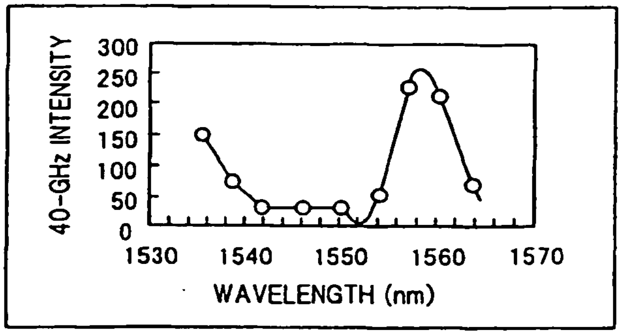


FIG.49B

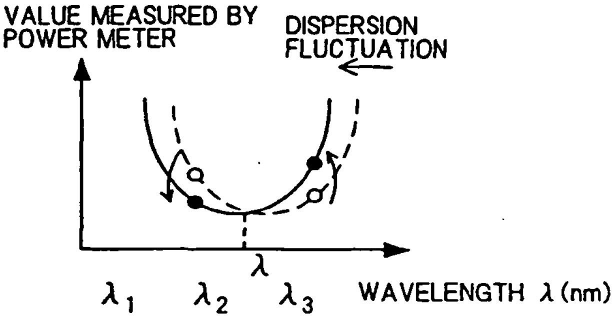

VALUE MEASURED BY POWER METER
DISPERSION FLUCTUATION
λ
λ1
λ2
λ3
WAVELENGTH λ (nm)

FIG.49C

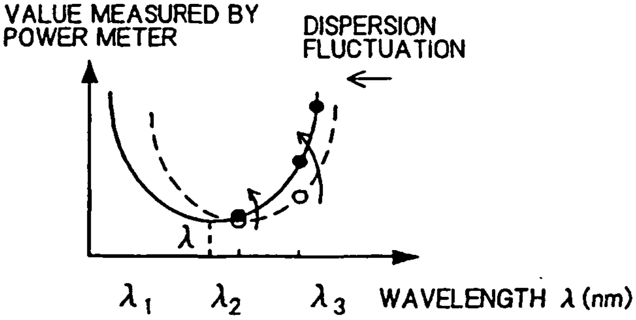

VALUE MEASURED BY POWER METER
DISPERSION FLUCTUATION
λ
λ1
λ2
λ3
WAVELENGTH λ (nm)

FIG.49D

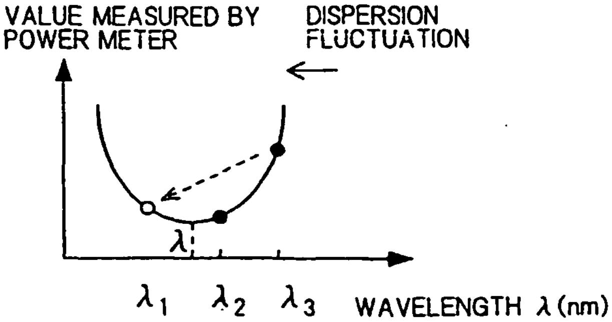

VALUE MEASURED BY POWER METER
DISPERSION FLUCTUATION
λ
λ1
λ2
λ3
WAVELENGTH λ (nm)

FIG. 50

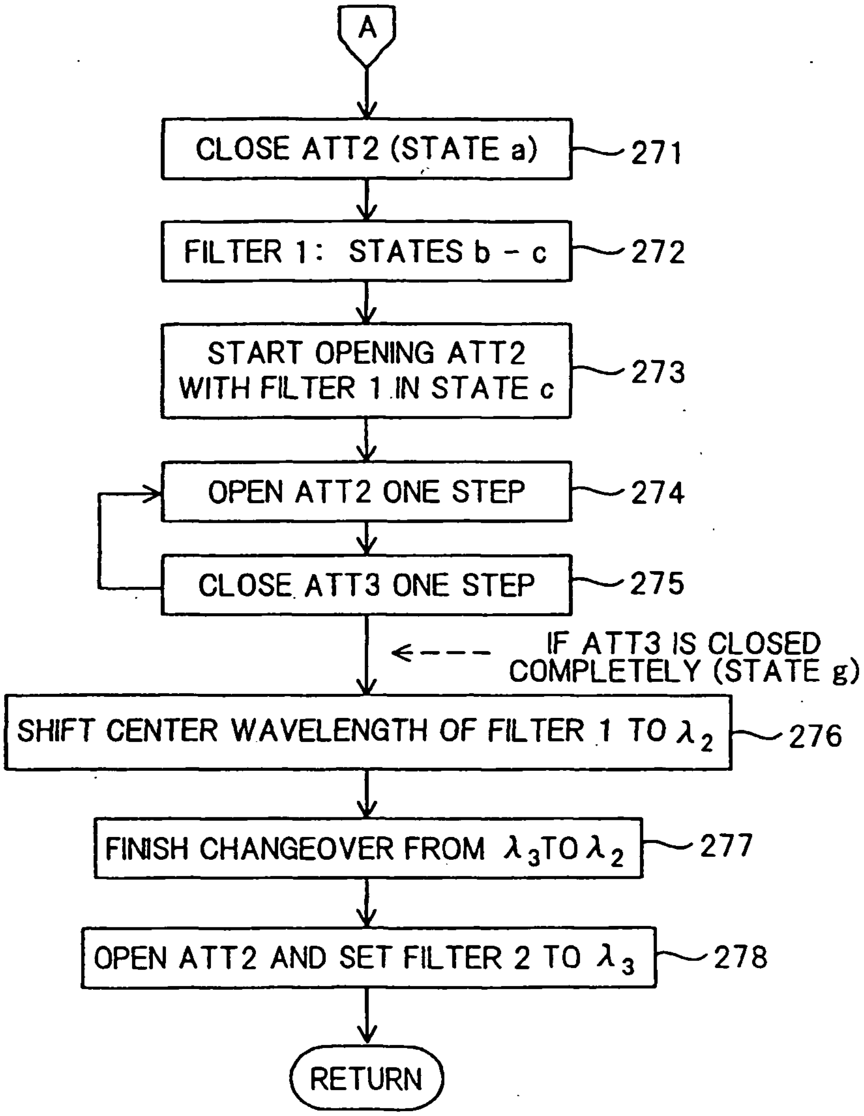

A
CLOSE ATT2 (STATE a)
271
FILTER 1: STATES b - c
272
START OPENING ATT2 WITH FILTER 1 IN STATE c
273
OPEN ATT2 ONE STEP
274
CLOSE ATT3 ONE STEP
275
IF ATT3 IS CLOSED COMPLETELY (STATE g)
SHIFT CENTER WAVELENGTH OF FILTER 1 TO λ2
276
FINISH CHANGEOVER FROM λ3 TO λ2
277
OPEN ATT2 AND SET FILTER 2 TO λ3
278
RETURN

FIG.51

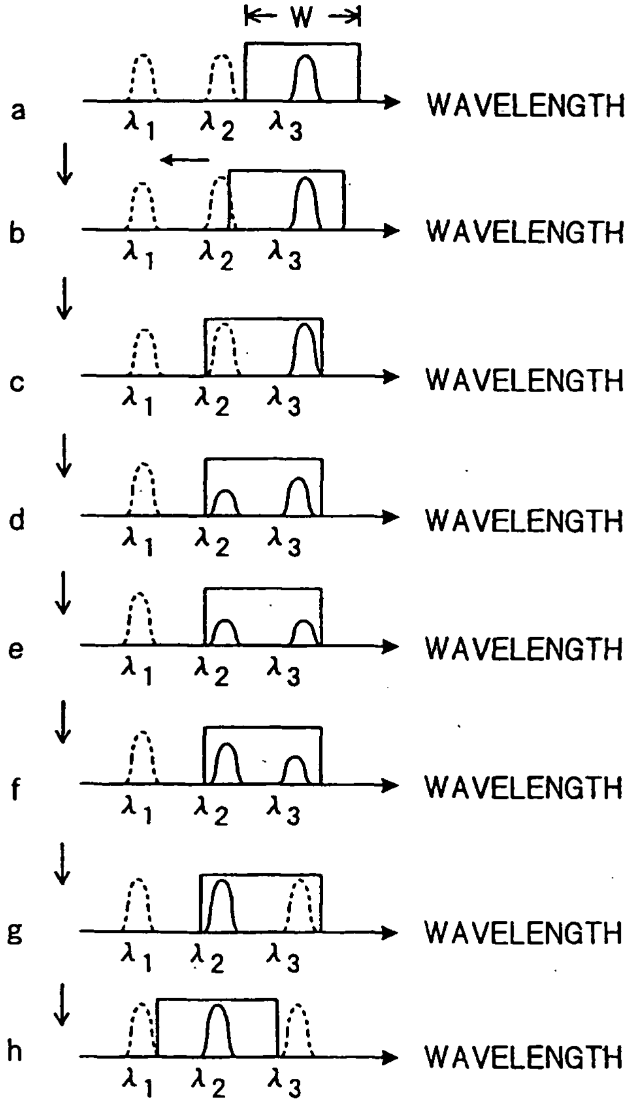

W
a
b
c
d
e
f
g
h
λ_1
λ_2
λ_3
WAVELENGTH

FIG.52A

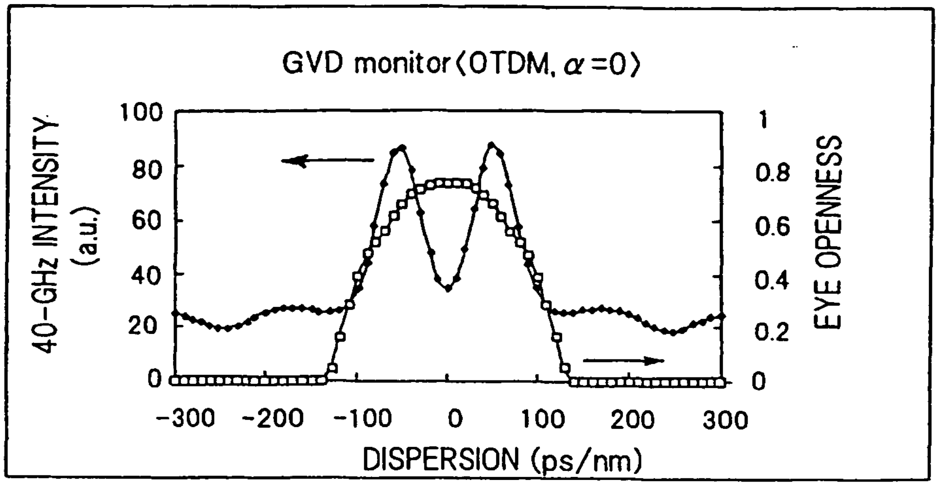


FIG.52B

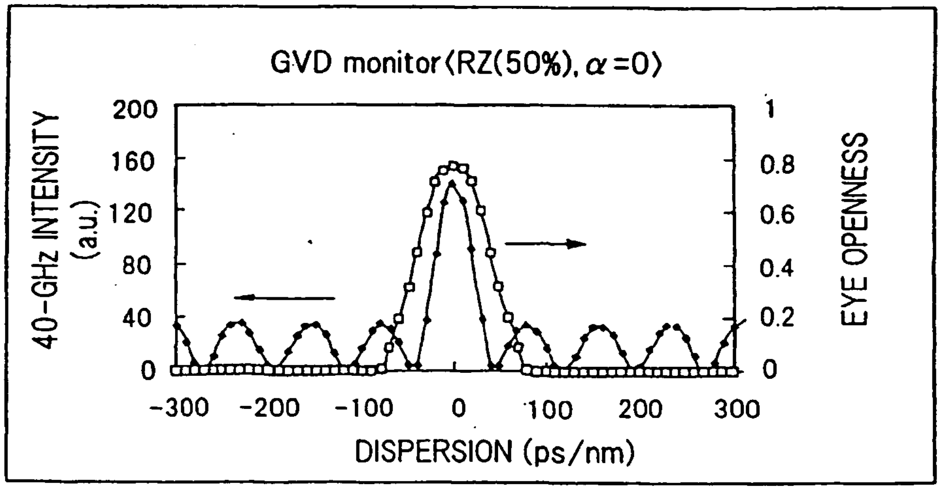


FIG.53

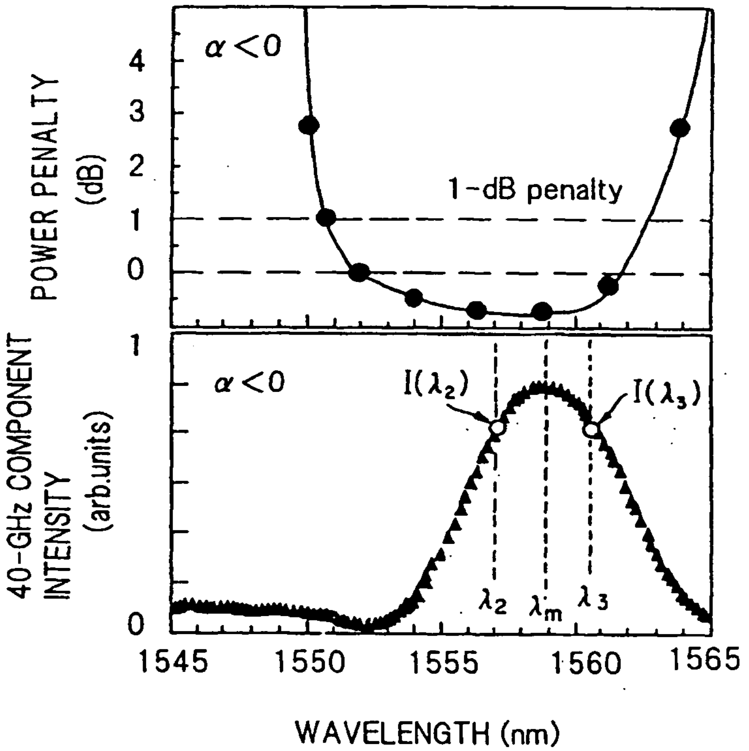

POWER PENALTY (dB)
4
3
2
1
0
$\alpha<0$
1-dB penalty
40-GHz COMPONENT INTENSITY (arb.units)
1
0
$\alpha<0$
$I(\lambda_2)$
$I(\lambda_3)$
λ_2
λ_m
λ_3
1545
1550
1555
1560
1565
WAVELENGTH (nm)

FIG.54A

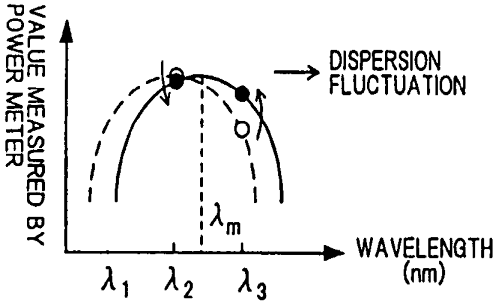


FIG.54B

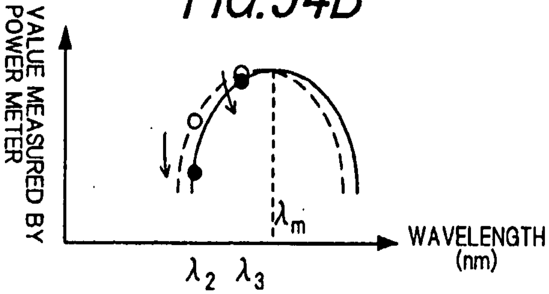


FIG.54C

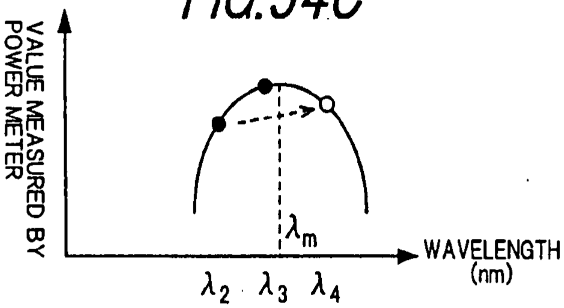


FIG.54D

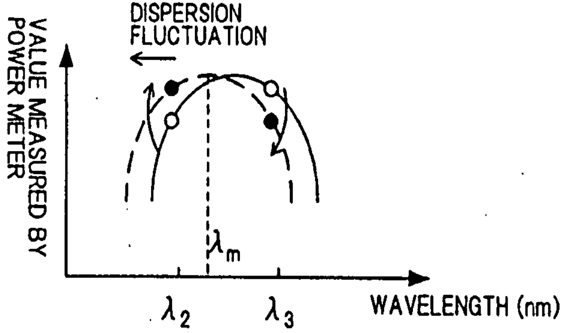


FIG.54E

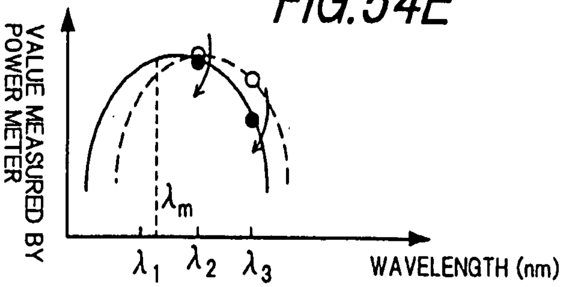


FIG.54F

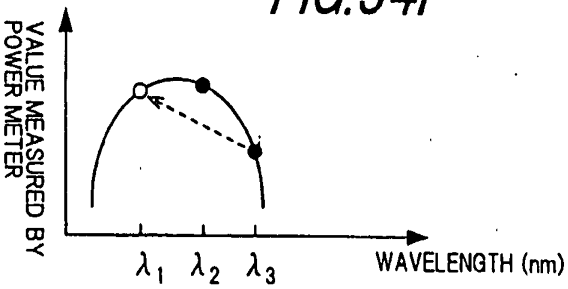
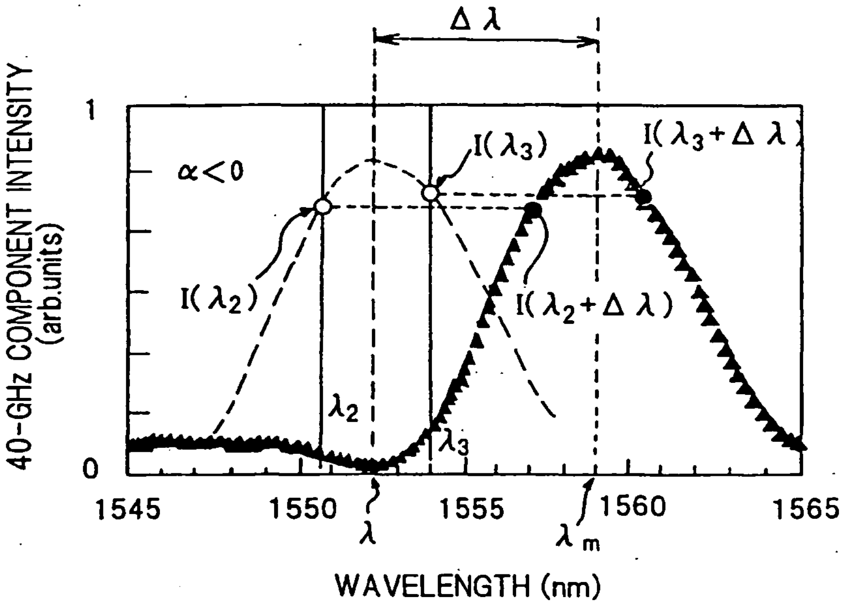


FIG. 55



Δ λ
40-GHz COMPONENT INTENSITY (arb.units)
1
0
α<0
I(λ3)
I(λ3+Δ λ)
I(λ2)
I(λ2+Δ λ)
λ2
λ3
1545
1550
1555
1560
1565
λ
λm
WAVELENGTH (nm)

FIG.56

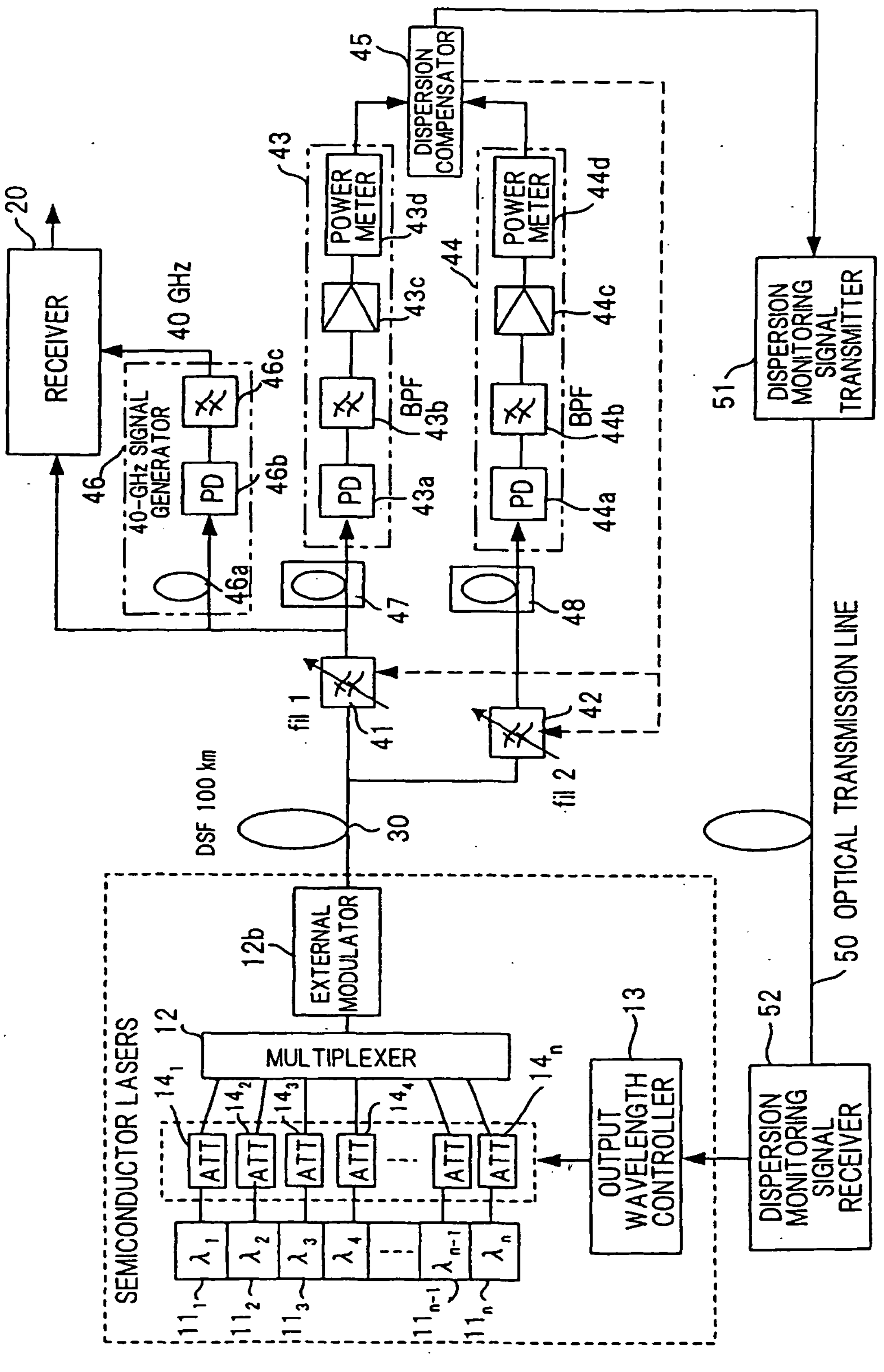

SEMICONDUCTOR LASERS
λ_1
λ_2
λ_3
λ_4
λ_{n-1}
λ_n
11_1
11_2
11_3
11_{n-1}
11_n
ATT
14_1
14_2
14_3
14_4
14_n
MULTIPLEXER
12
EXTERNAL MODULATOR
12b
OUTPUT WAVELENGTH CONTROLLER
13
DISPERSION MONITORING SIGNAL RECEIVER
52
50 OPTICAL TRANSMISSION LINE
DISPERSION MONITORING SIGNAL TRANSMITTER
51
DSF 100 km
30
fil 1
41
fil 2
42
47
48
RECEIVER
20
40 GHz
40-GHz SIGNAL GENERATOR
46
46a
PD
46b
46c
43
PD
43a
BPF
43b
43c
POWER METER
43d
44
44a
44b
44c
44d
DISPERSION COMPENSATOR
45

FIG.57

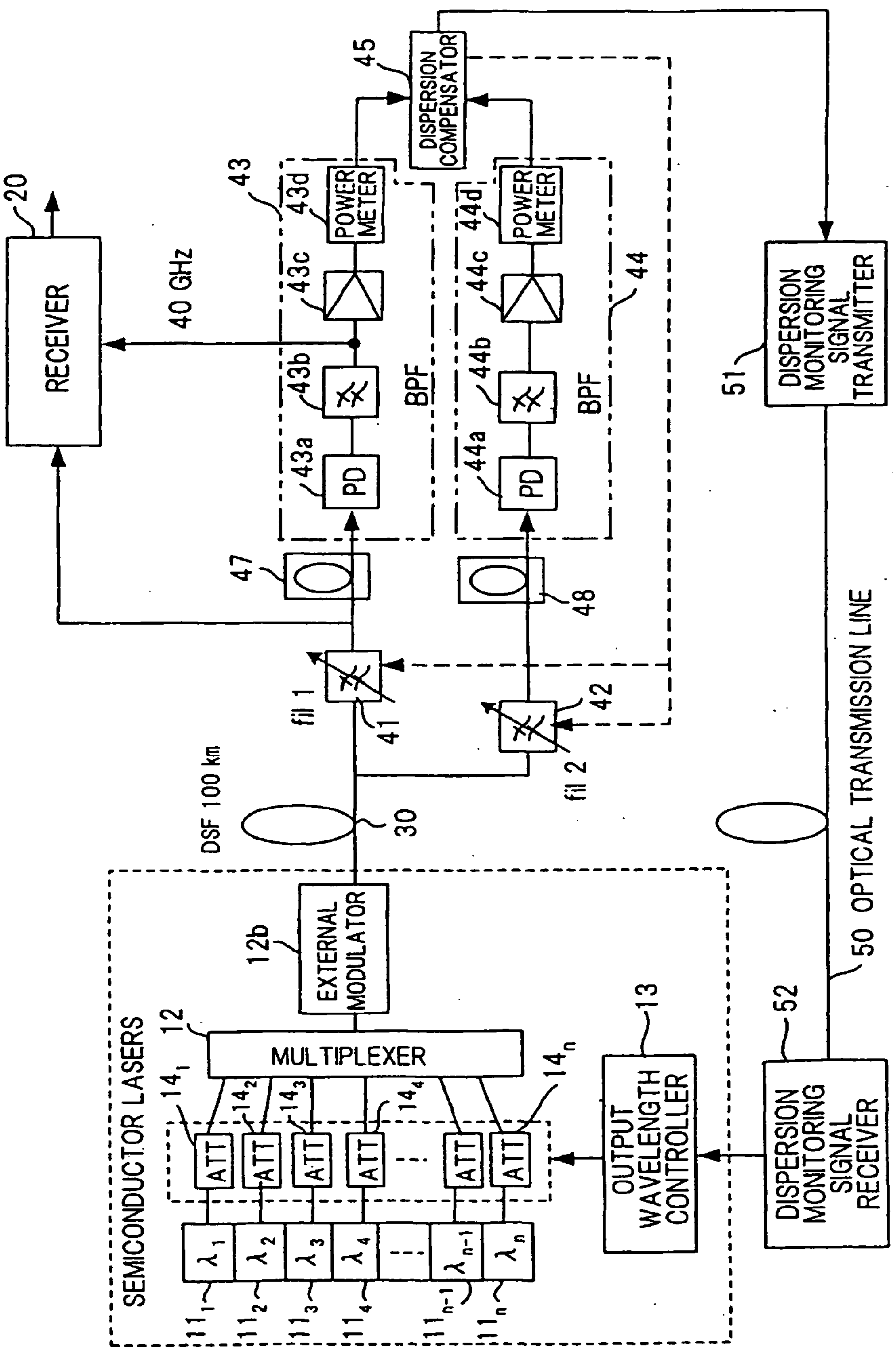

RECEIVER
20
40 GHz
43
43a
43b
43c
43d
PD
BPF
POWER METER
44
44a
44b
44c
44d
PD
BPF
POWER METER
45
DISPERSION COMPENSATOR
47
48
fil 1
41
fil 2
42
DSF 100 km
30
EXTERNAL MODULATOR
12b
MULTIPLEXER
12
14_1
14_2
14_3
14_4
14_n
ATT
ATT
ATT
ATT
ATT
ATT
λ_1
λ_2
λ_3
λ_4
λ_{n-1}
λ_n
11_1
11_2
11_3
11_4
11_{n-1}
11_n
SEMICONDUCTOR LASERS
OUTPUT WAVELENGTH CONTROLLER
13
DISPERSION MONITORING SIGNAL RECEIVER
52
50 OPTICAL TRANSMISSION LINE
DISPERSION MONITORING SIGNAL TRANSMITTER
51

FIG.58

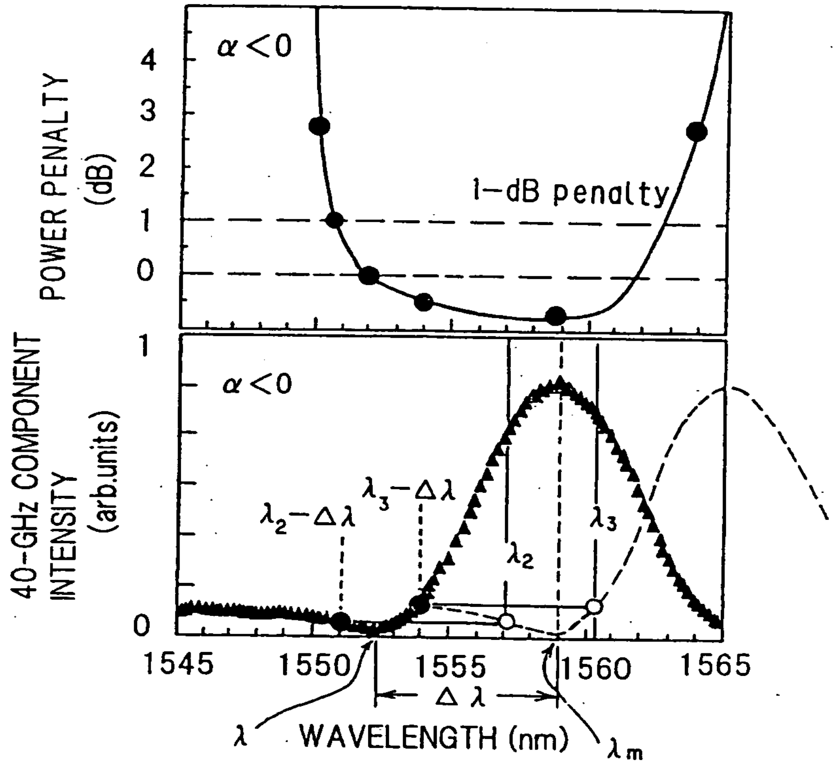

POWER PENALTY (dB)
4
3
2
1
0
α<0
1-dB penalty
40-GHz COMPONENT INTENSITY (arb.units)
1
0
α<0
$\lambda_2-\Delta\lambda$
$\lambda_3-\Delta\lambda$
λ_2
λ_3
1545
1550
1555
1560
1565
Δλ
λ
WAVELENGTH (nm)
λ_m

FIG. 59A

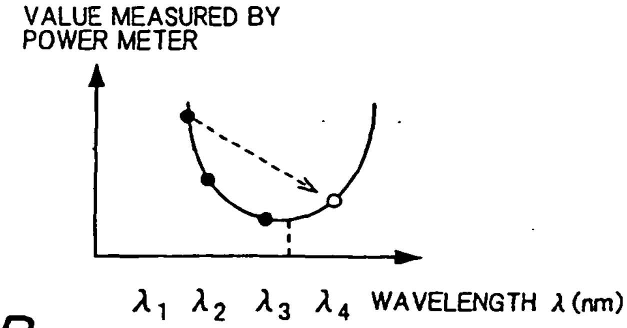


FIG. 59B

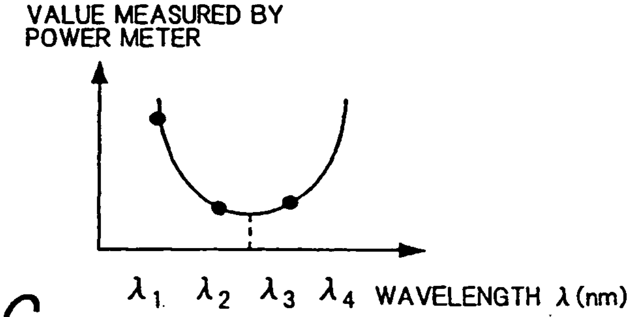


FIG. 59C

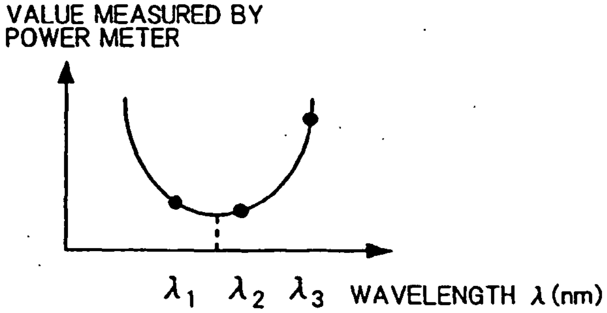


FIG. 59D

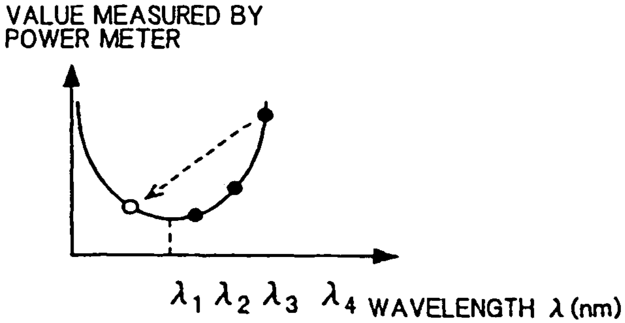


FIG.60

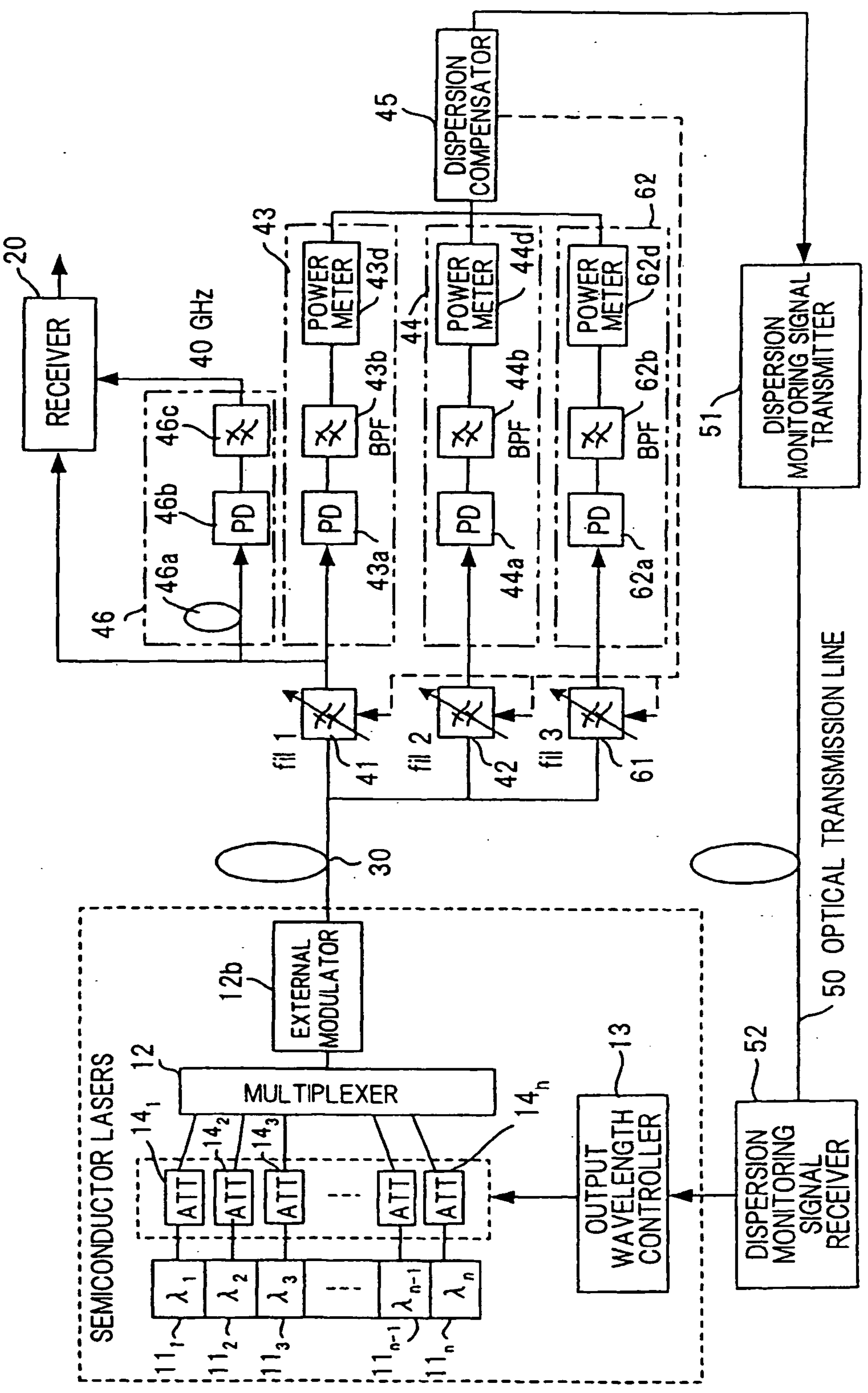

SEMICONDUCTOR LASERS
λ_1
λ_2
λ_3
λ_{n-1}
λ_n
11_1
11_2
11_3
11_{n-1}
11_n
ATT
ATT
ATT
ATT
ATT
14_1
14_2
14_3
14_n
MULTIPLEXER
12
EXTERNAL MODULATOR
12b
OUTPUT WAVELENGTH CONTROLLER
13
DISPERSION MONITORING SIGNAL RECEIVER
52
30
50 OPTICAL TRANSMISSION LINE
fil 1
fil 2
fil 3
41
42
61
46
46a
46b
46c
PD
40 GHz
RECEIVER
20
43
43a
PD
BPF
43b
POWER METER
43d
44
44a
PD
BPF
44b
POWER METER
44d
62
62a
PD
BPF
62b
POWER METER
62d
DISPERSION COMPENSATOR
45
DISPERSION MONITORING SIGNAL TRANSMITTER
51

FIG.61

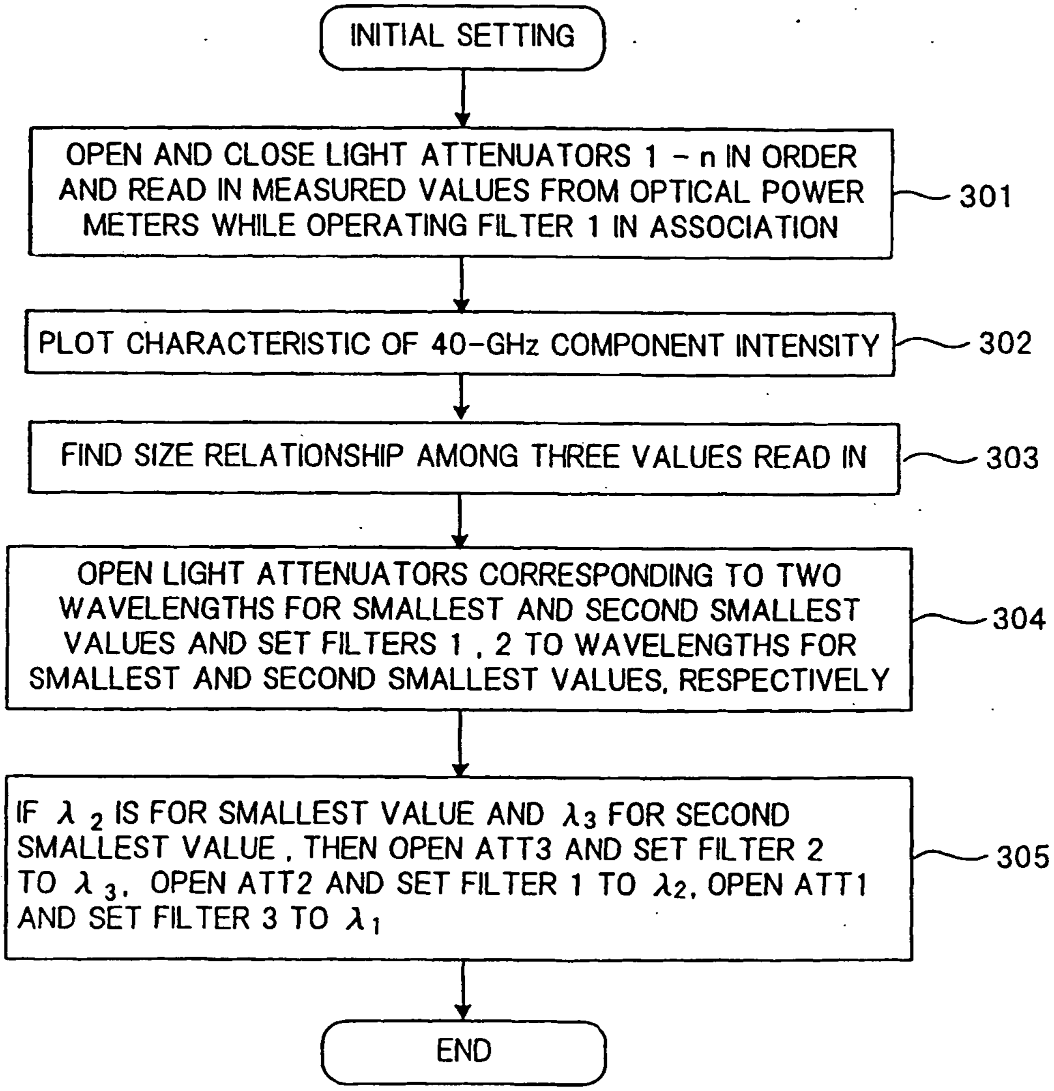

INITIAL SETTING
OPEN AND CLOSE LIGHT ATTENUATORS 1 - n IN ORDER AND READ IN MEASURED VALUES FROM OPTICAL POWER METERS WHILE OPERATING FILTER 1 IN ASSOCIATION
301
PLOT CHARACTERISTIC OF 40-GHz COMPONENT INTENSITY
302
FIND SIZE RELATIONSHIP AMONG THREE VALUES READ IN
303
OPEN LIGHT ATTENUATORS CORRESPONDING TO TWO WAVELENGTHS FOR SMALLEST AND SECOND SMALLEST VALUES AND SET FILTERS 1 , 2 TO WAVELENGTHS FOR SMALLEST AND SECOND SMALLEST VALUES, RESPECTIVELY
304
IF λ_2 IS FOR SMALLEST VALUE AND λ_3 FOR SECOND SMALLEST VALUE , THEN OPEN ATT3 AND SET FILTER 2 TO λ_3, OPEN ATT2 AND SET FILTER 1 TO λ_2, OPEN ATT1 AND SET FILTER 3 TO λ_1
305
END

FIG.62

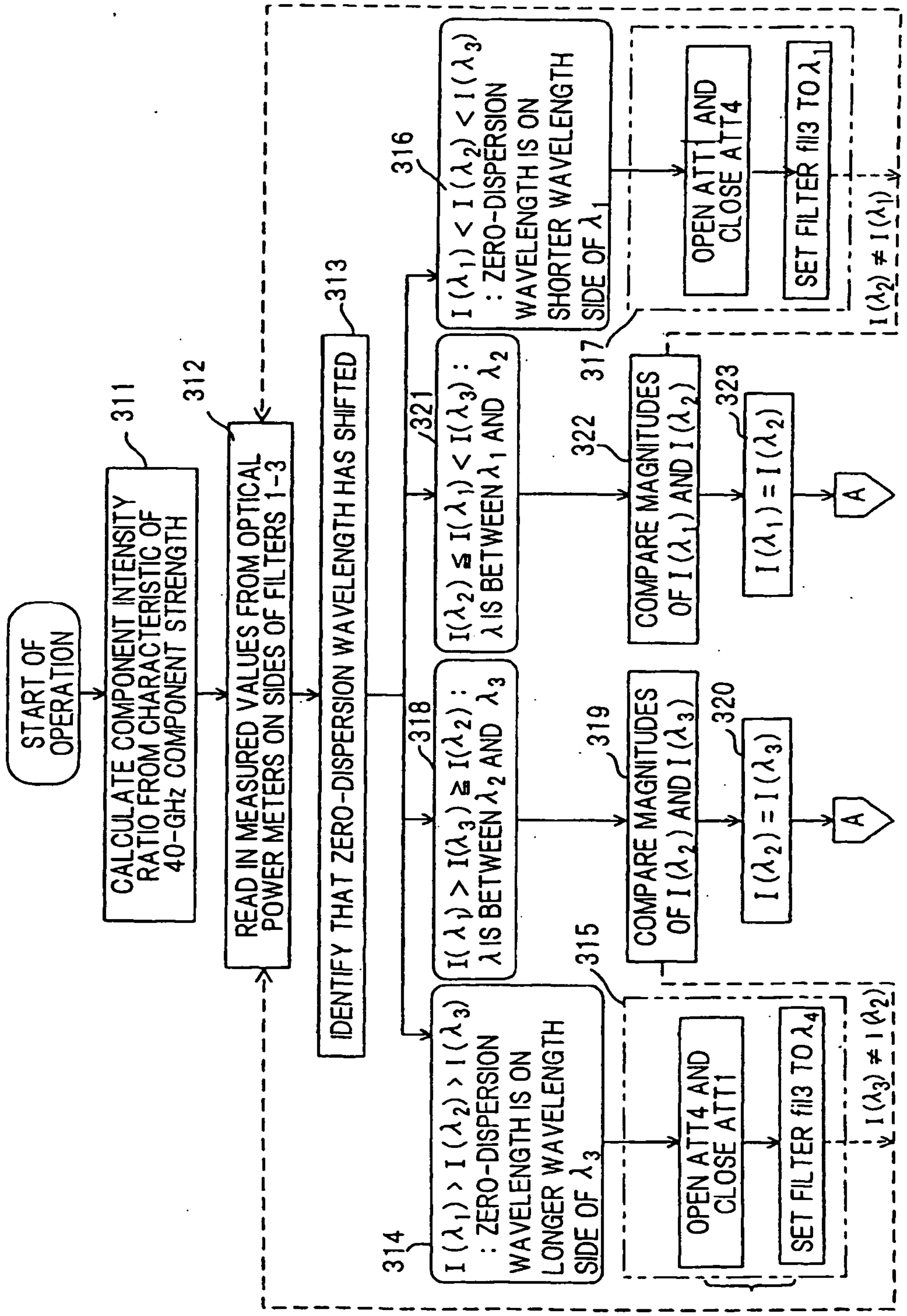

START OF OPERATION
311
CALCULATE COMPONENT INTENSITY RATIO FROM CHARACTERISTIC OF 40-GHz COMPONENT STRENGTH
312
READ IN MEASURED VALUES FROM OPTICAL POWER METERS ON SIDES OF FILTERS 1-3
313
IDENTIFY THAT ZERO-DISPERSION WAVELENGTH HAS SHIFTED
314
$I(\lambda_1) > I(\lambda_2) > I(\lambda_3)$: ZERO-DISPERSION WAVELENGTH IS ON LONGER WAVELENGTH SIDE OF λ_3
318
$I(\lambda_1) > I(\lambda_3) \geqq I(\lambda_2)$: λ IS BETWEEN λ_2 AND λ_3
321
$I(\lambda_2) \leqq I(\lambda_1) < I(\lambda_3)$: λ IS BETWEEN λ_1 AND λ_2
316
$I(\lambda_1) < I(\lambda_2) < I(\lambda_3)$: ZERO-DISPERSION WAVELENGTH IS ON SHORTER WAVELENGTH SIDE OF λ_1
315
OPEN ATT4 AND CLOSE ATT1
SET FILTER fil3 TO λ_4
$I(\lambda_3) \neq I(\lambda_2)$
319
COMPARE MAGNITUDES OF $I(\lambda_2)$ AND $I(\lambda_3)$
320
$I(\lambda_2) = I(\lambda_3)$
A
322
COMPARE MAGNITUDES OF $I(\lambda_1)$ AND $I(\lambda_2)$
323
$I(\lambda_1) = I(\lambda_2)$
A
317
OPEN ATT1 AND CLOSE ATT4
SET FILTER fil3 TO λ_1
$I(\lambda_2) \neq I(\lambda_1)$

FIG.63

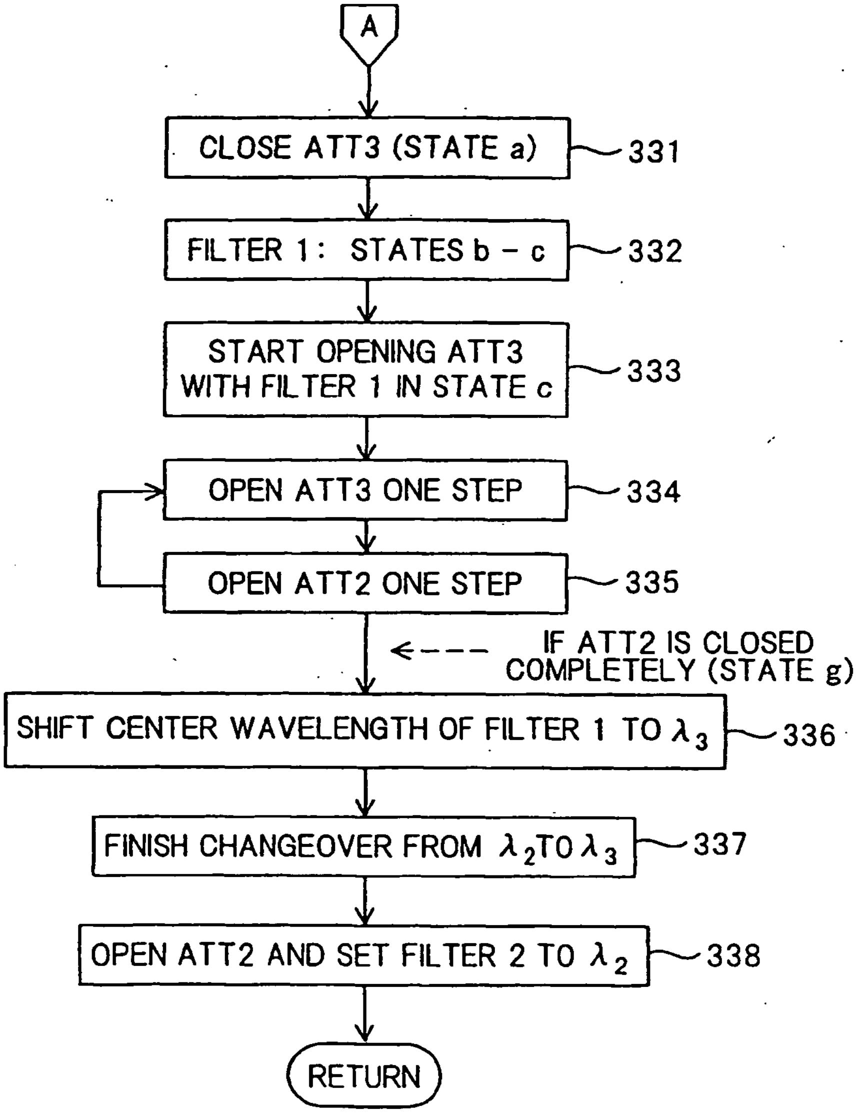

A
CLOSE ATT3 (STATE a)
331
FILTER 1 : STATES b – c
332
START OPENING ATT3 WITH FILTER 1 IN STATE c
333
OPEN ATT3 ONE STEP
334
OPEN ATT2 ONE STEP
335
IF ATT2 IS CLOSED COMPLETELY (STATE g)
SHIFT CENTER WAVELENGTH OF FILTER 1 TO λ3
336
FINISH CHANGEOVER FROM λ2 TO λ3
337
OPEN ATT2 AND SET FILTER 2 TO λ2
338
RETURN

FIG. 64

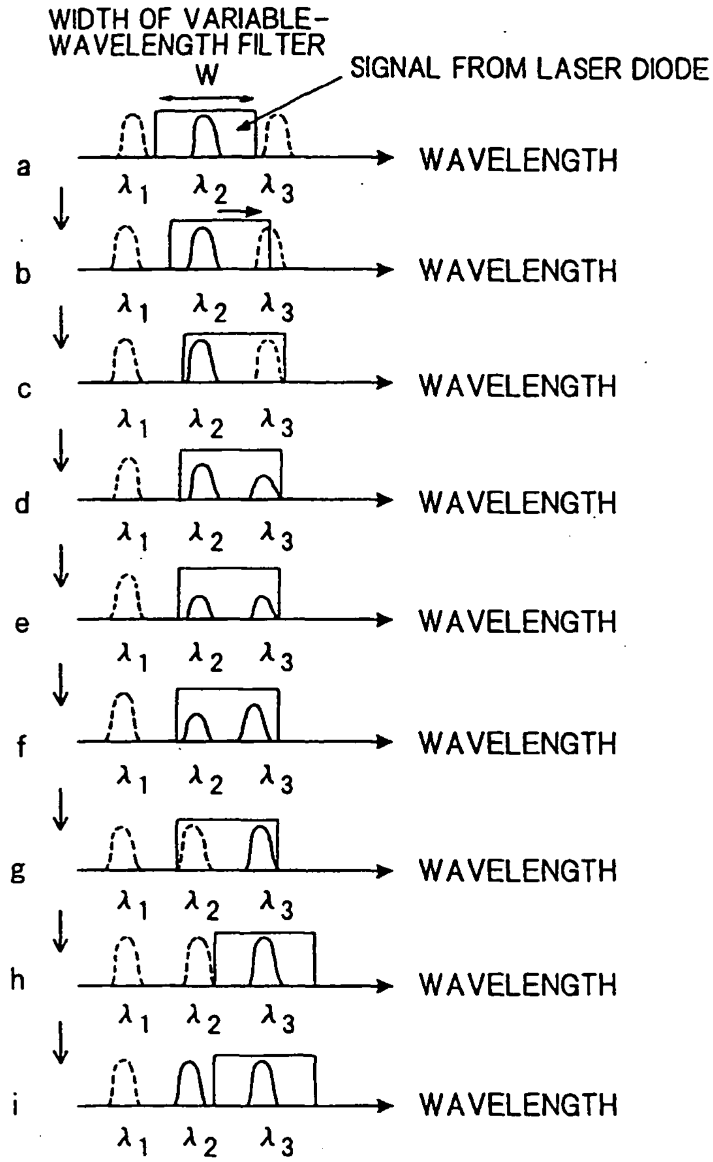

WIDTH OF VARIABLE-WAVELENGTH FILTER
W
SIGNAL FROM LASER DIODE
a
b
c
d
e
f
g
h
i
WAVELENGTH
λ1
λ2
λ3

FIG.65

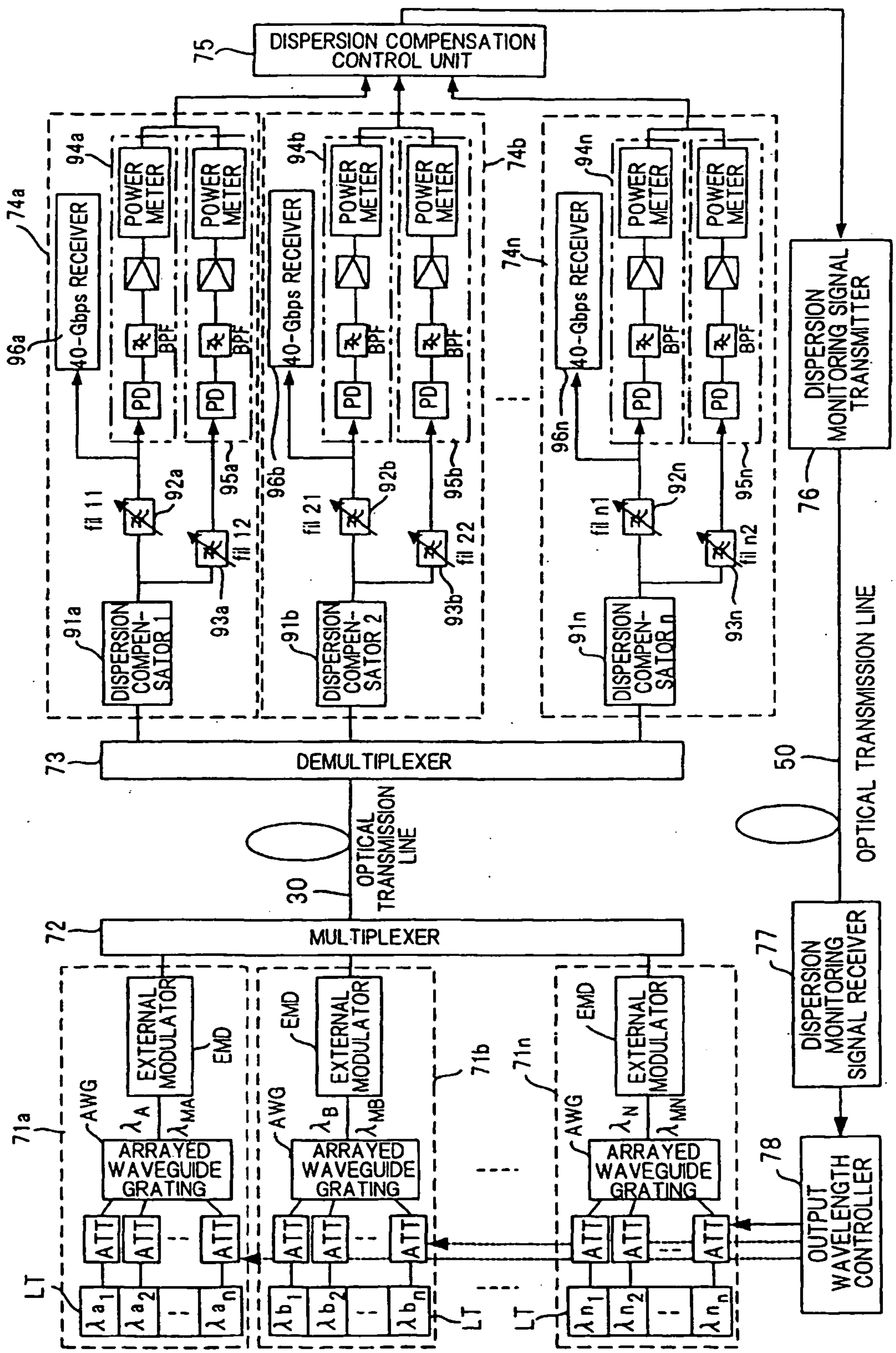

75
DISPERSION COMPENSATION CONTROL UNIT
74a
96a
40-Gbps RECEIVER
94a
POWER METER
POWER METER
BPF
BPF
PD
PD
fil 11
92a
95a
fil 12
93a
91a
DISPERSION COMPEN-SATOR 1
74b
94b
96b
40-Gbps RECEIVER
92b
95b
fil 21
fil 22
93b
91b
DISPERSION COMPEN-SATOR 2
74n
94n
96n
40-Gbps RECEIVER
fil n1
92n
95n
fil n2
93n
91n
DISPERSION COMPEN-SATOR n
76
DISPERSION MONITORING SIGNAL TRANSMITTER
73
DEMULTIPLEXER
30
OPTICAL TRANSMISSION LINE
50
OPTICAL TRANSMISSION LINE
72
MULTIPLEXER
77
DISPERSION MONITORING SIGNAL RECEIVER
78
OUTPUT WAVELENGTH CONTROLLER
71a
71b
71n
EXTERNAL MODULATOR
EMD
AWG
λ_A
λ_{MA}
λ_B
λ_{MB}
λ_N
λ_{MN}
ARRAYED WAVEGUIDE GRATING
ATT
LT
λa_1
λa_2
λa_n
λb_1
λb_2
λb_n
λn_1
λn_2
λn_n

FIG.66A

INITIAL STATE

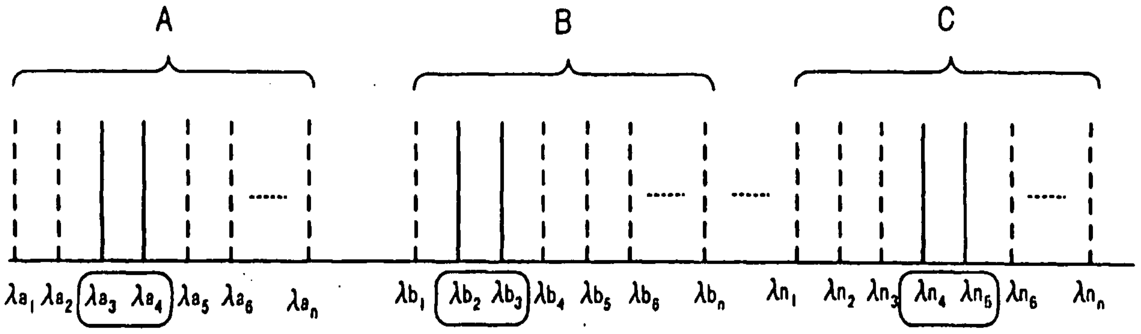

A
B
C
λa1 λa2 λa3 λa4 λa5 λa6 λan
λb1 λb2 λb3 λb4 λb5 λb6 λbn
λn1 λn2 λn3 λn4 λn5 λn6 λnn

FIG.66B

WHEN OPTIMUM WAVELENGTH HAS SHIFTED TOWARD SIDE OF SHORTER WAVELENGTH

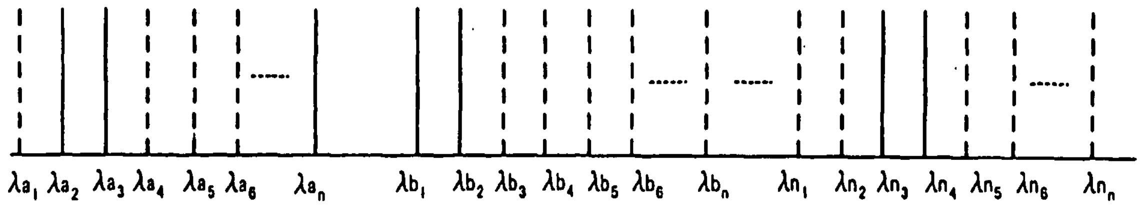

λa1 λa2 λa3 λa4 λa5 λa6 λan
λb1 λb2 λb3 λb4 λb5 λb6 λbn
λn1 λn2 λn3 λn4 λn5 λn6 λnn

FIG.66C

WHEN OPTIMUM WAVELENGTH HAS SHIFTED TOWARD SIDE OF LONGER WAVELENGTH

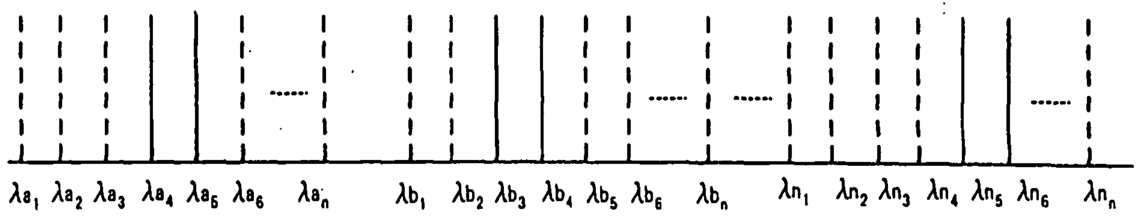

λa1 λa2 λa3 λa4 λa5 λa6 λan
λb1 λb2 λb3 λb4 λb5 λb6 λbn
λn1 λn2 λn3 λn4 λn5 λn6 λnn

FIG.67

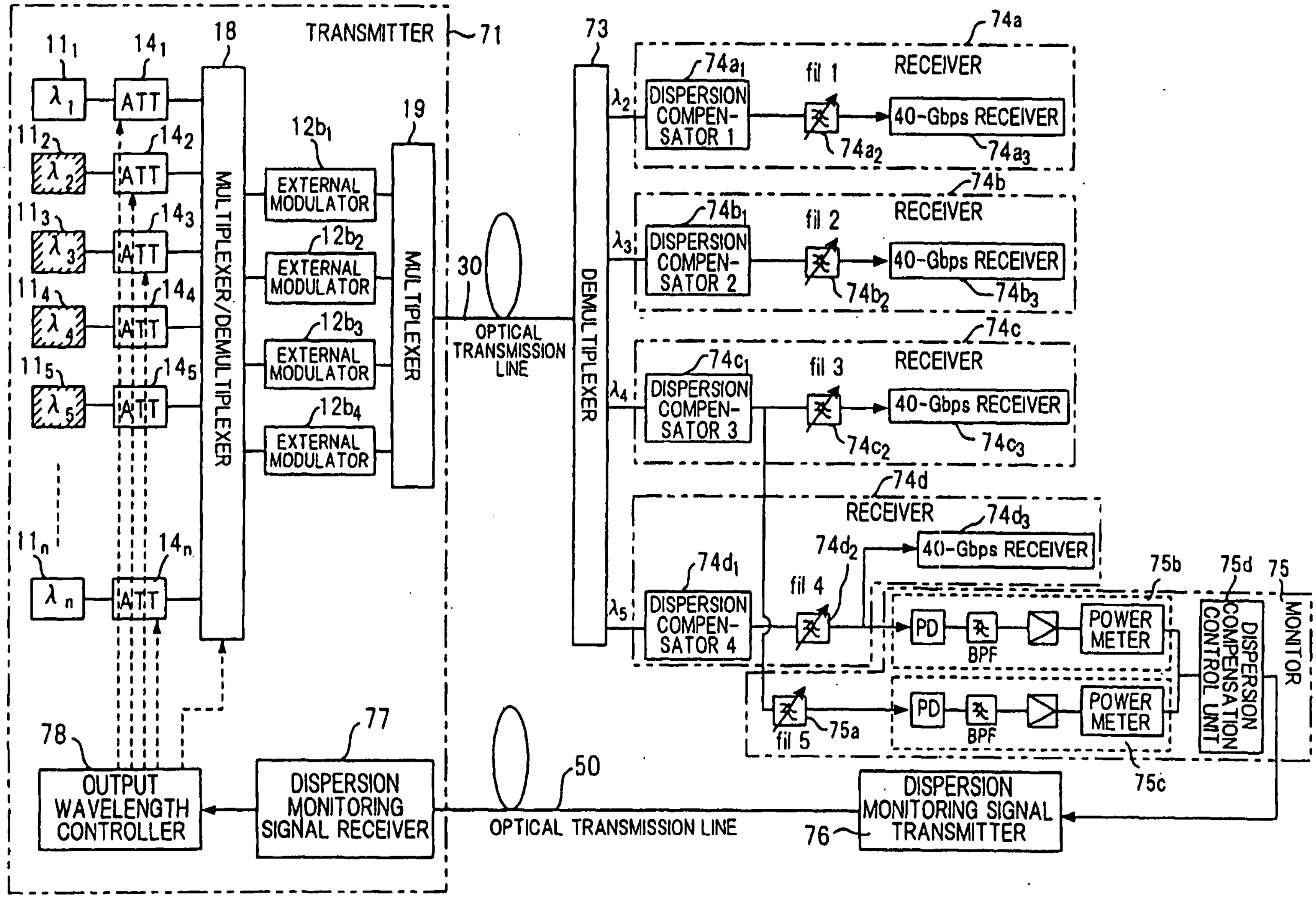

TRANSMITTER
71
11_1
λ_1
14_1
ATT
11_2
λ_2
14_2
11_3
λ_3
14_3
11_4
λ_4
14_4
11_5
λ_5
14_5
11_n
λ_n
14_n
18
MULTIPLEXER/DEMULTIPLEXER
$12b_1$
$12b_2$
$12b_3$
$12b_4$
EXTERNAL MODULATOR
19
MULTIPLEXER
30
OPTICAL TRANSMISSION LINE
73
DEMULTIPLEXER
λ_2
λ_3
λ_4
λ_5
74a
RECEIVER
$74a_1$
DISPERSION COMPEN-SATOR 1
fil 1
$74a_2$
40-Gbps RECEIVER
$74a_3$
74b
RECEIVER
$74b_1$
DISPERSION COMPEN-SATOR 2
fil 2
$74b_2$
40-Gbps RECEIVER
$74b_3$
74c
RECEIVER
$74c_1$
DISPERSION COMPEN-SATOR 3
fil 3
$74c_2$
40-Gbps RECEIVER
$74c_3$
74d
RECEIVER
$74d_1$
DISPERSION COMPEN-SATOR 4
fil 4
$74d_2$
40-Gbps RECEIVER
$74d_3$
fil 5
75a
PD
BPF
POWER METER
75b
75c
75d
DISPERSION COMPENSATION CONTROL UNIT
75
MONITOR
76
DISPERSION MONITORING SIGNAL TRANSMITTER
50
OPTICAL TRANSMISSION LINE
77
DISPERSION MONITORING SIGNAL RECEIVER
78
OUTPUT WAVELENGTH CONTROLLER

FIG.68

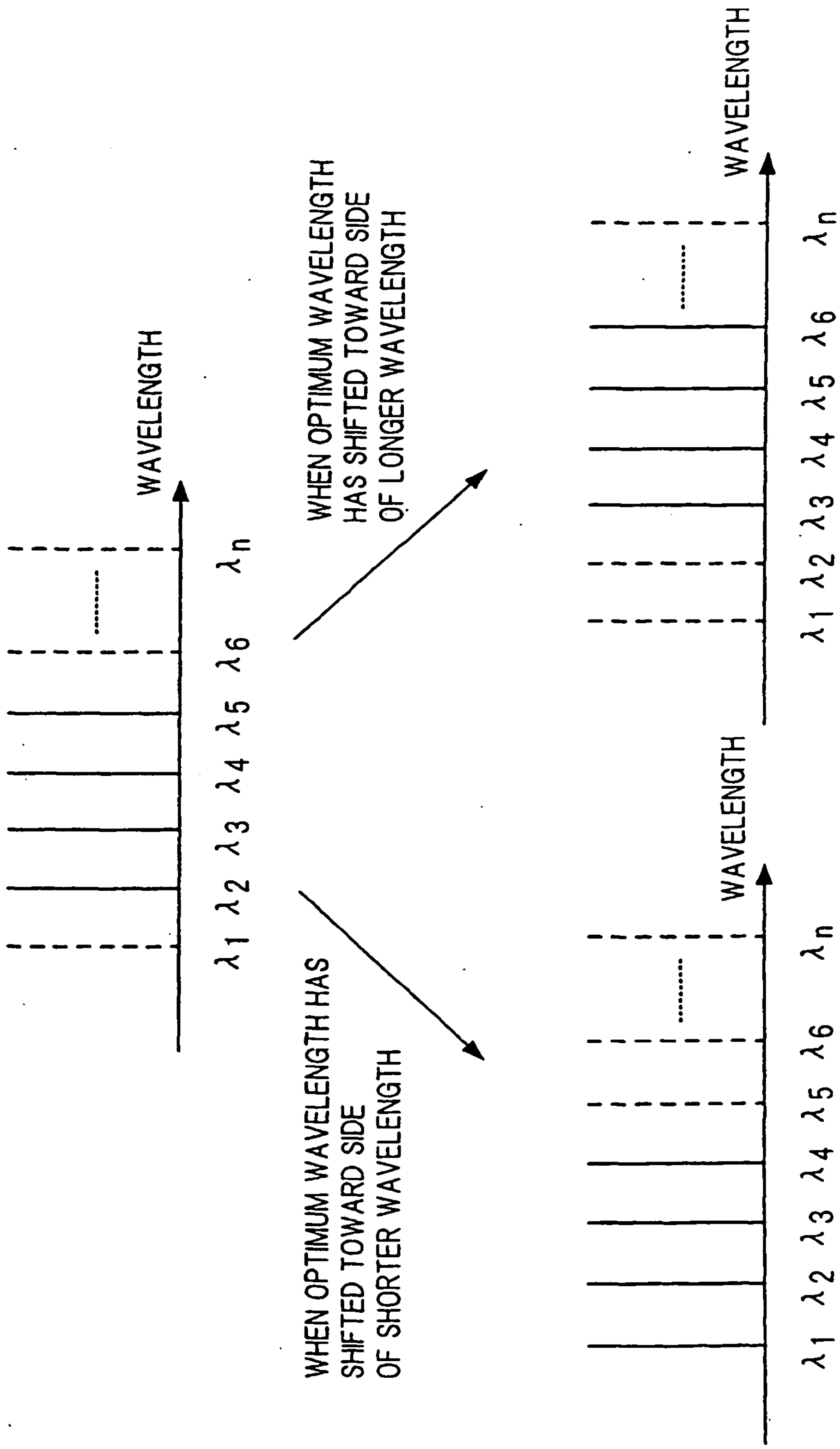

WAVELENGTH
λ1 λ2 λ3 λ4 λ5 λ6 λn
WHEN OPTIMUM WAVELENGTH HAS SHIFTED TOWARD SIDE OF LONGER WAVELENGTH
WHEN OPTIMUM WAVELENGTH HAS SHIFTED TOWARD SIDE OF SHORTER WAVELENGTH
WAVELENGTH
λ1 λ2 λ3 λ4 λ5 λ6 λn
WAVELENGTH
λ1 λ2 λ3 λ4 λ5 λ6 λn

FIG.69

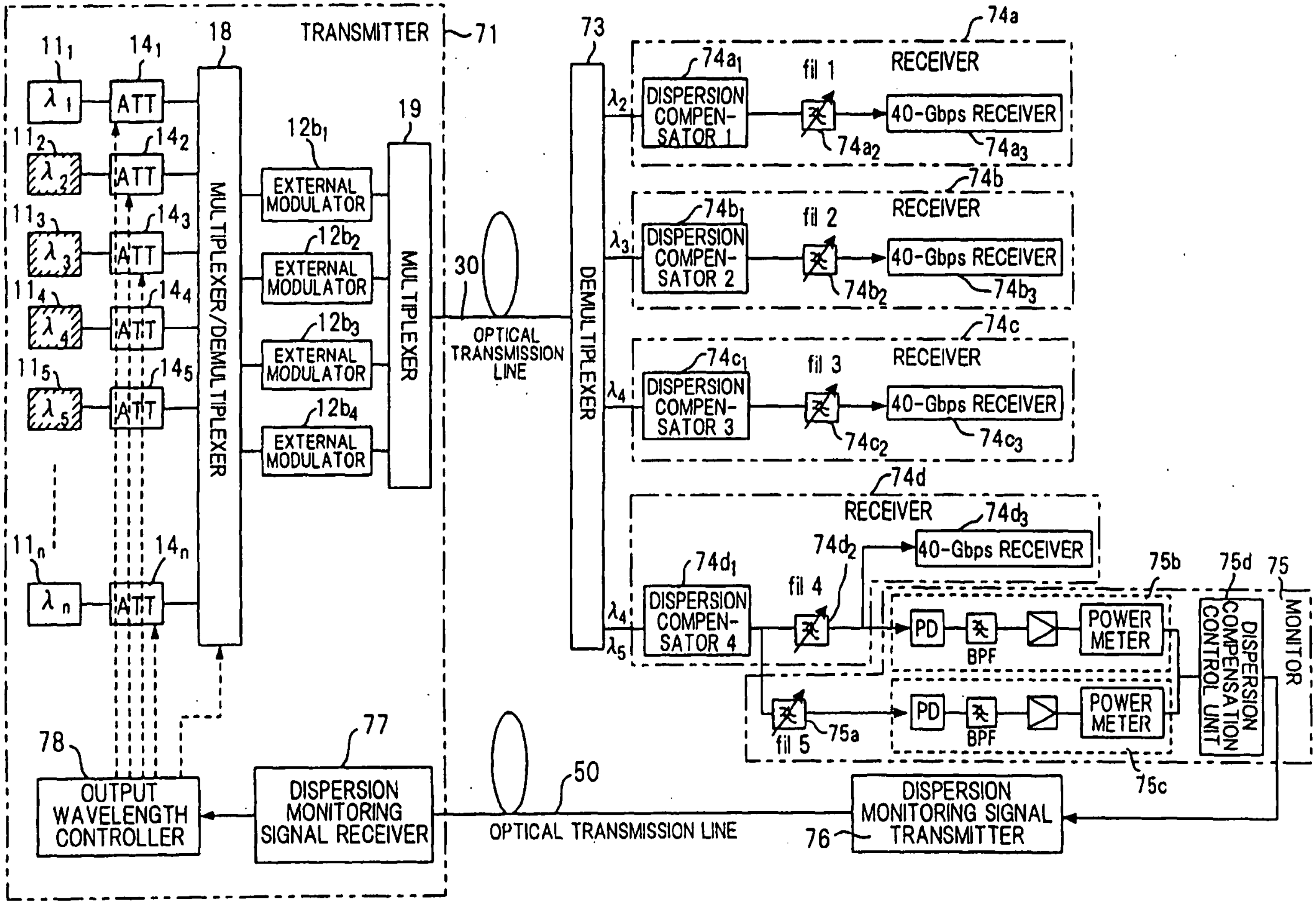

TRANSMITTER
71
11_1
14_1
18
λ_1
ATT
11_2
14_2
λ_2
11_3
14_3
λ_3
11_4
14_4
λ_4
11_5
14_5
λ_5
11_n
14_n
λ_n
MULTIPLEXER/DEMULTIPLEXER
$12b_1$
$12b_2$
$12b_3$
$12b_4$
EXTERNAL MODULATOR
19
MULTIPLEXER
30
OPTICAL TRANSMISSION LINE
73
DEMULTIPLEXER
λ_2
λ_3
λ_4
λ_4
λ_5
74a
$74a_1$
DISPERSION COMPEN-SATOR 1
fil 1
RECEIVER
40-Gbps RECEIVER
$74a_2$
$74a_3$
74b
$74b_1$
DISPERSION COMPEN-SATOR 2
fil 2
$74b_2$
$74b_3$
74c
$74c_1$
DISPERSION COMPEN-SATOR 3
fil 3
$74c_2$
$74c_3$
74d
$74d_1$
DISPERSION COMPEN-SATOR 4
fil 4
$74d_2$
$74d_3$
75b
75d
75
MONITOR
PD
BPF
POWER METER
DISPERSION COMPENSATION CONTROL UNIT
fil 5
75a
75c
78
OUTPUT WAVELENGTH CONTROLLER
77
DISPERSION MONITORING SIGNAL RECEIVER
50
OPTICAL TRANSMISSION LINE
76
DISPERSION MONITORING SIGNAL TRANSMITTER

FIG. 70

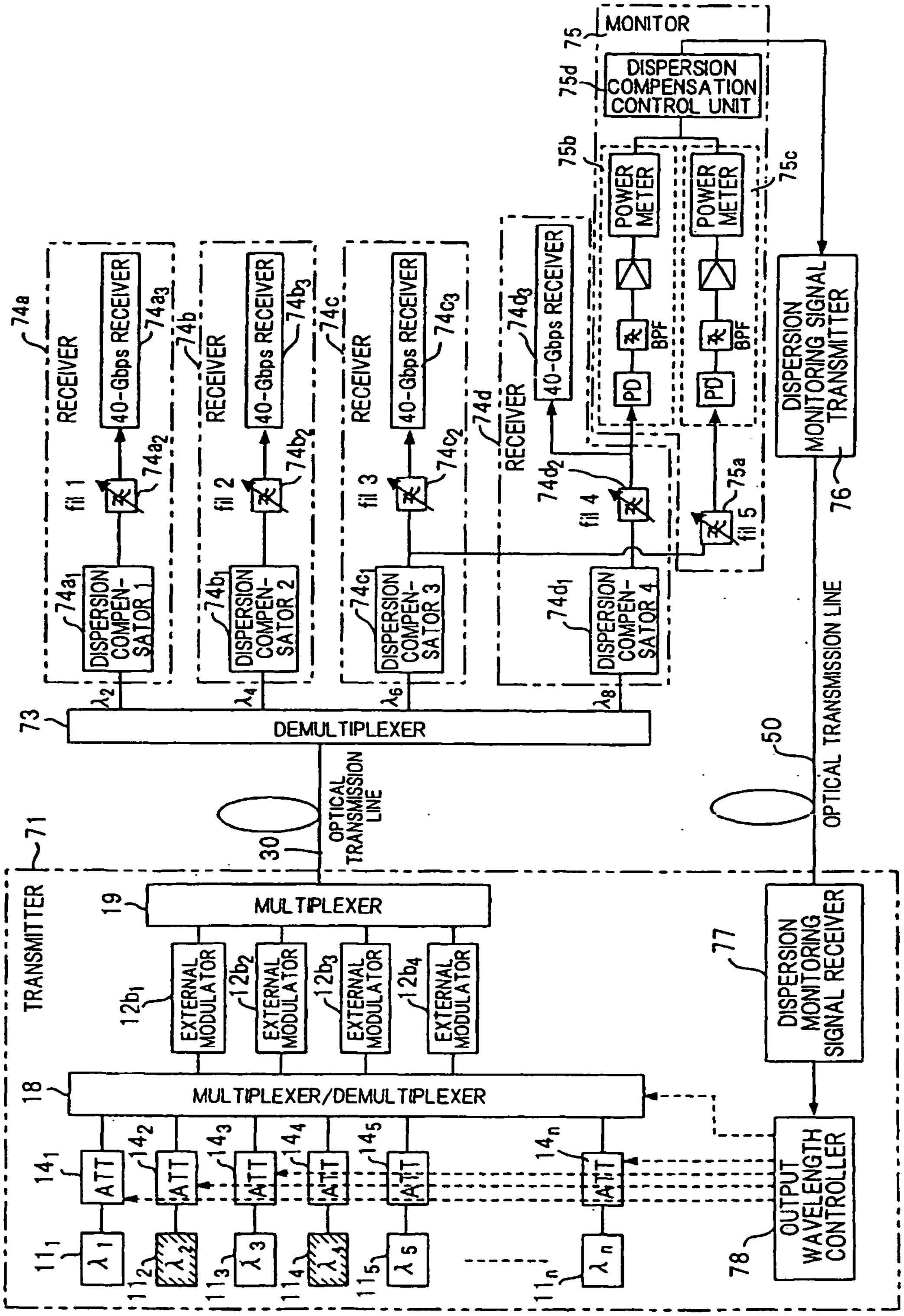

MONITOR
75
75d
DISPERSION COMPENSATION CONTROL UNIT
75b
75c
POWER METER
POWER METER
BPF
BPF
PD
PD
75a
fil 5
fil 4
74d
74d1
74d2
74d3
RECEIVER
40-Gbps RECEIVER
DISPERSION COMPEN-SATOR 4
74a
74a1
74a2
74a3
RECEIVER
40-Gbps RECEIVER
fil 1
DISPERSION COMPEN-SATOR 1
74b
74b1
74b2
74b3
RECEIVER
40-Gbps RECEIVER
fil 2
DISPERSION COMPEN-SATOR 2
74c
74c1
74c2
74c3
RECEIVER
40-Gbps RECEIVER
fil 3
DISPERSION COMPEN-SATOR 3
λ2
λ4
λ6
λ8
73
DEMULTIPLEXER
30
OPTICAL TRANSMISSION LINE
50
OPTICAL TRANSMISSION LINE
76
DISPERSION MONITORING SIGNAL TRANSMITTER
71
TRANSMITTER
19
MULTIPLEXER
12b1
12b2
12b3
12b4
EXTERNAL MODULATOR
EXTERNAL MODULATOR
EXTERNAL MODULATOR
EXTERNAL MODULATOR
77
DISPERSION MONITORING SIGNAL RECEIVER
18
MULTIPLEXER/DEMULTIPLEXER
141
142
143
144
145
14n
ATT
ATT
ATT
ATT
ATT
ATT
111
112
113
114
115
11n
λ1
λ2
λ3
λ4
λ5
λn
78
OUTPUT WAVELENGTH CONTROLLER

FIG.71

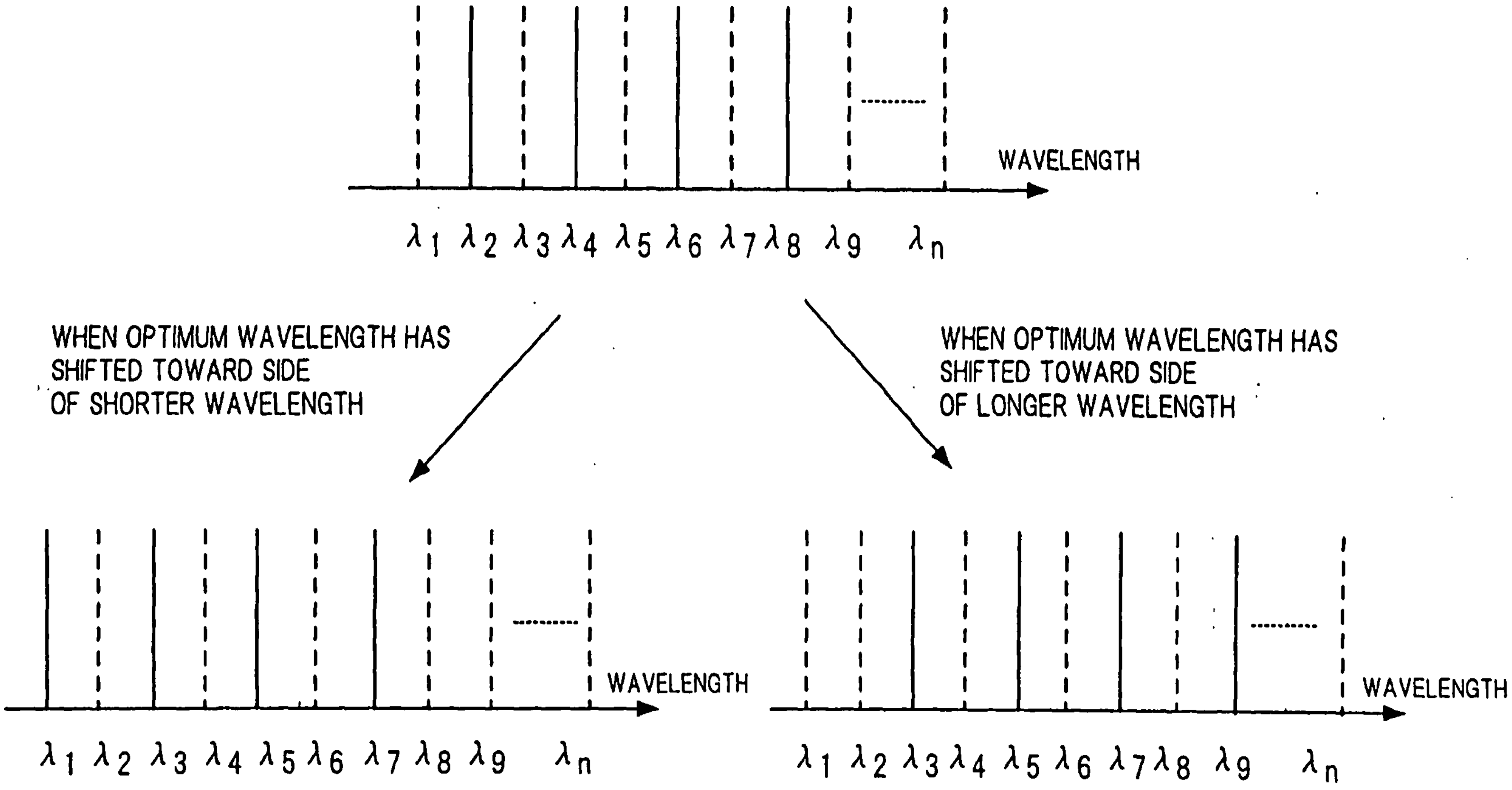

WAVELENGTH
λ1 λ2 λ3 λ4 λ5 λ6 λ7 λ8 λ9 λn
WHEN OPTIMUM WAVELENGTH HAS SHIFTED TOWARD SIDE OF SHORTER WAVELENGTH
WHEN OPTIMUM WAVELENGTH HAS SHIFTED TOWARD SIDE OF LONGER WAVELENGTH
WAVELENGTH
λ1 λ2 λ3 λ4 λ5 λ6 λ7 λ8 λ9 λn
WAVELENGTH
λ1 λ2 λ3 λ4 λ5 λ6 λ7 λ8 λ9 λn

FIG. 72

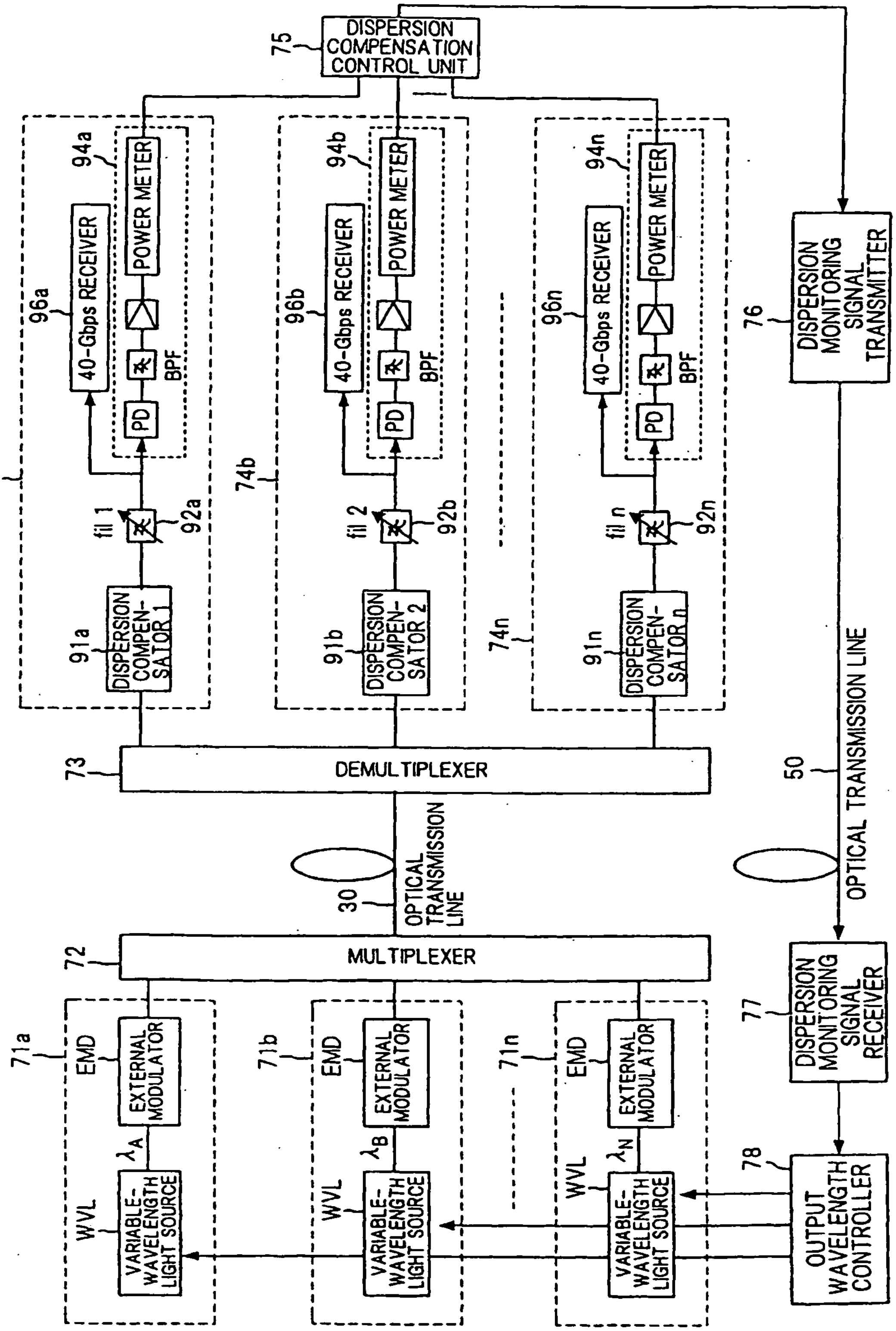

75
DISPERSION COMPENSATION CONTROL UNIT
74a
74b
74n
94a
94b
94n
POWER METER
96a
96b
96n
40-Gbps RECEIVER
BPF
PD
fil 1
fil 2
fil n
92a
92b
92n
91a
91b
91n
DISPERSION COMPEN-SATOR 1
DISPERSION COMPEN-SATOR 2
DISPERSION COMPEN-SATOR n
76
DISPERSION MONITORING SIGNAL TRANSMITTER
73
DEMULTIPLEXER
30
OPTICAL TRANSMISSION LINE
50
OPTICAL TRANSMISSION LINE
72
MULTIPLEXER
71a
71b
71n
EMD
EXTERNAL MODULATOR
λ_A
λ_B
λ_N
WVL
VARIABLE-WAVELENGTH LIGHT SOURCE
77
DISPERSION MONITORING SIGNAL RECEIVER
78
OUTPUT WAVELENGTH CONTROLLER

FIG. 73

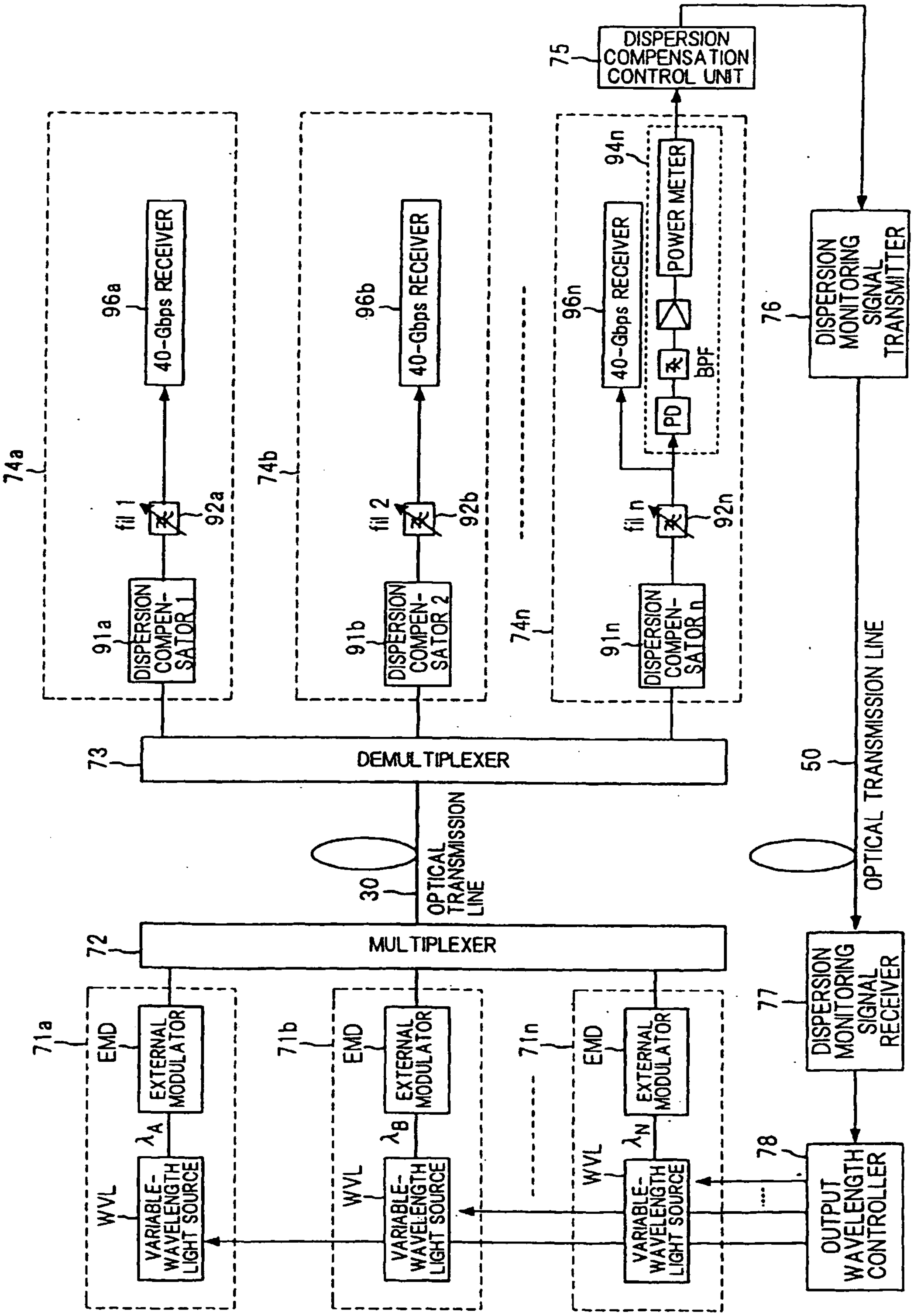

71a
71b
71n
WVL
EMD
VARIABLE-WAVELENGTH LIGHT SOURCE
EXTERNAL MODULATOR
λ_A
λ_B
λ_N
72
MULTIPLEXER
30
OPTICAL TRANSMISSION LINE
73
DEMULTIPLEXER
74a
74b
74n
91a
91b
91n
DISPERSION COMPEN-SATOR 1
DISPERSION COMPEN-SATOR 2
DISPERSION COMPEN-SATOR n
fil 1
fil 2
fil n
92a
92b
92n
96a
96b
96n
40-Gbps RECEIVER
PD
BPF
POWER METER
94n
75
DISPERSION COMPENSATION CONTROL UNIT
76
DISPERSION MONITORING SIGNAL TRANSMITTER
50
OPTICAL TRANSMISSION LINE
77
DISPERSION MONITORING SIGNAL RECEIVER
78
OUTPUT WAVELENGTH CONTROLLER

FIG. 74A

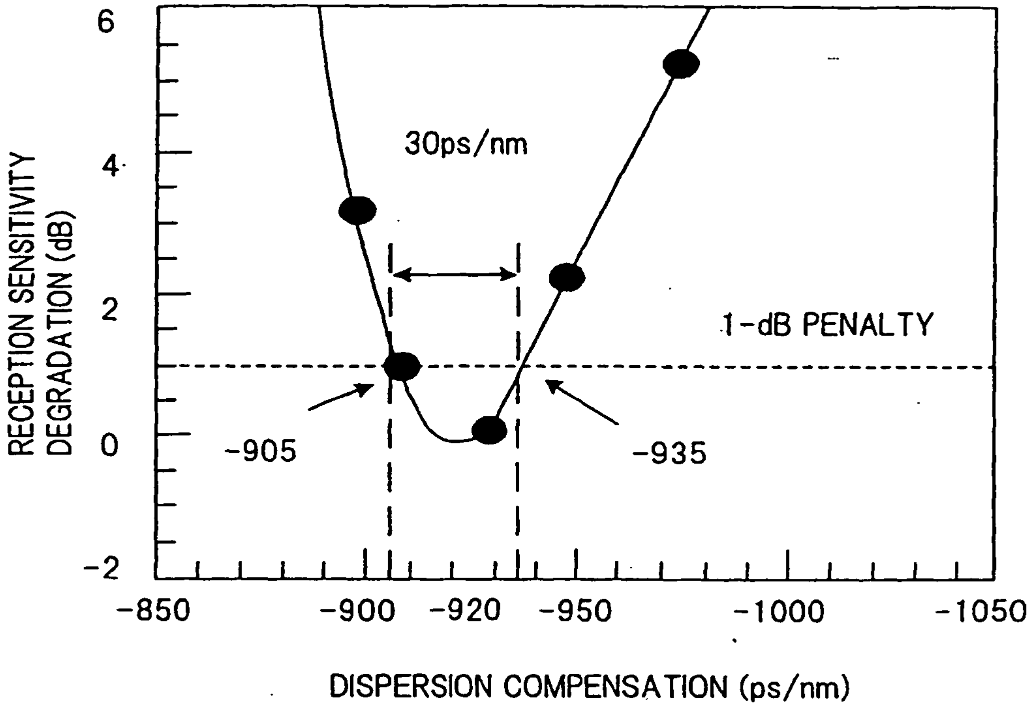


FIG. 74B

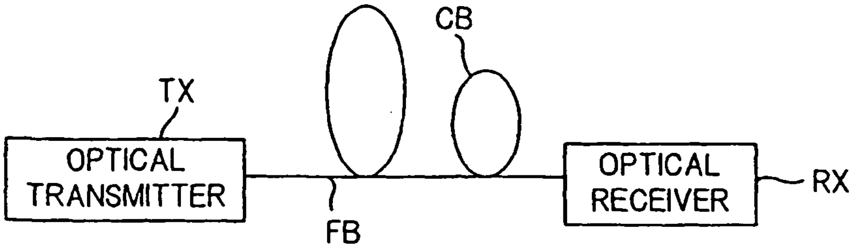

TX
OPTICAL TRANSMITTER
CB
FB
OPTICAL RECEIVER
RX

FIG. 75

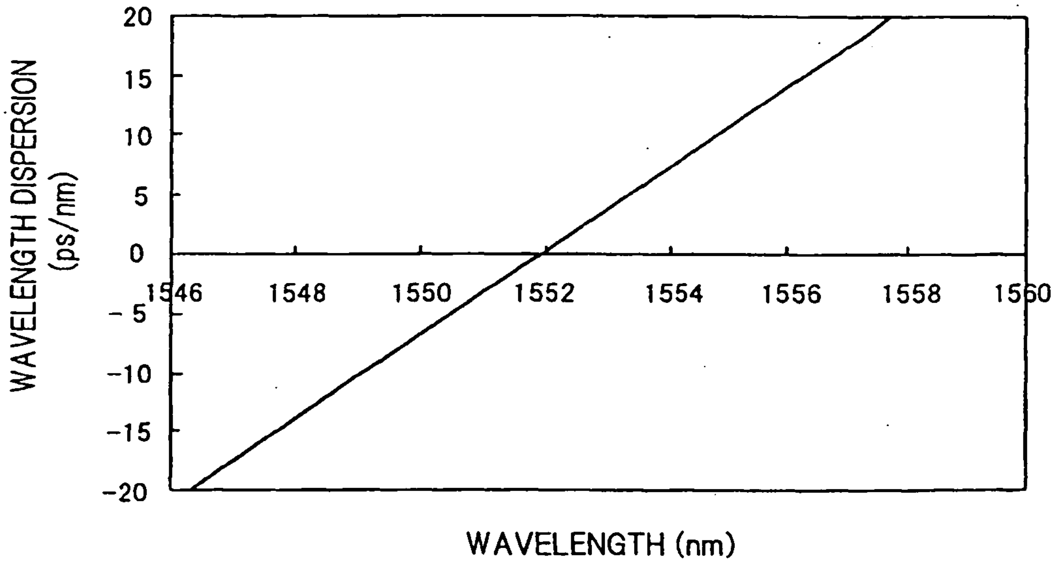

20
15
10
5
0
- 5
-10
-15
-20
WAVELENGTH DISPERSION (ps/nm)
1546
1548
1550
1552
1554
1556
1558
1560
WAVELENGTH (nm)

FIG. 76A

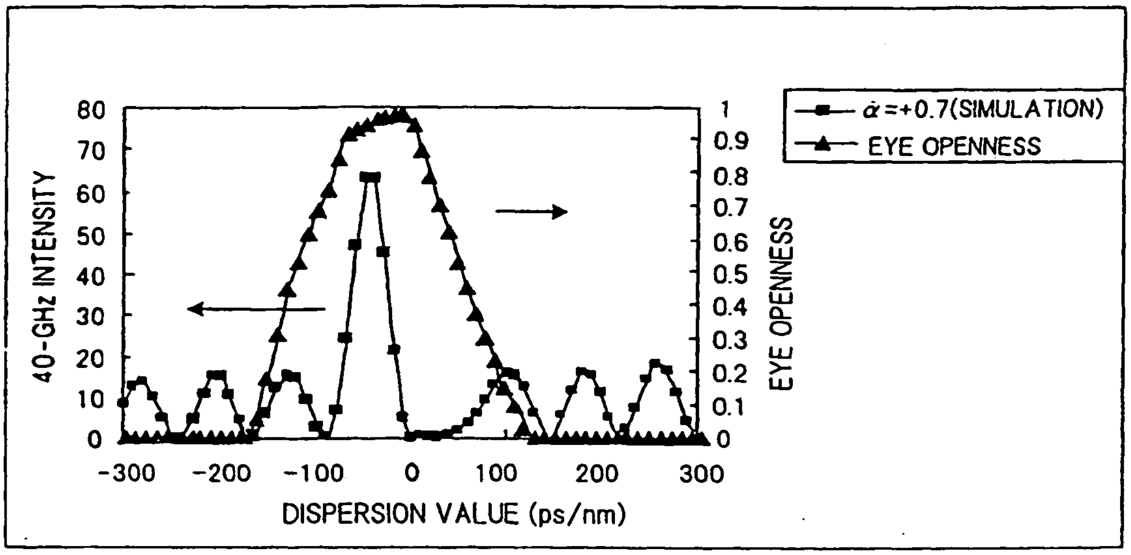


FIG. 76B

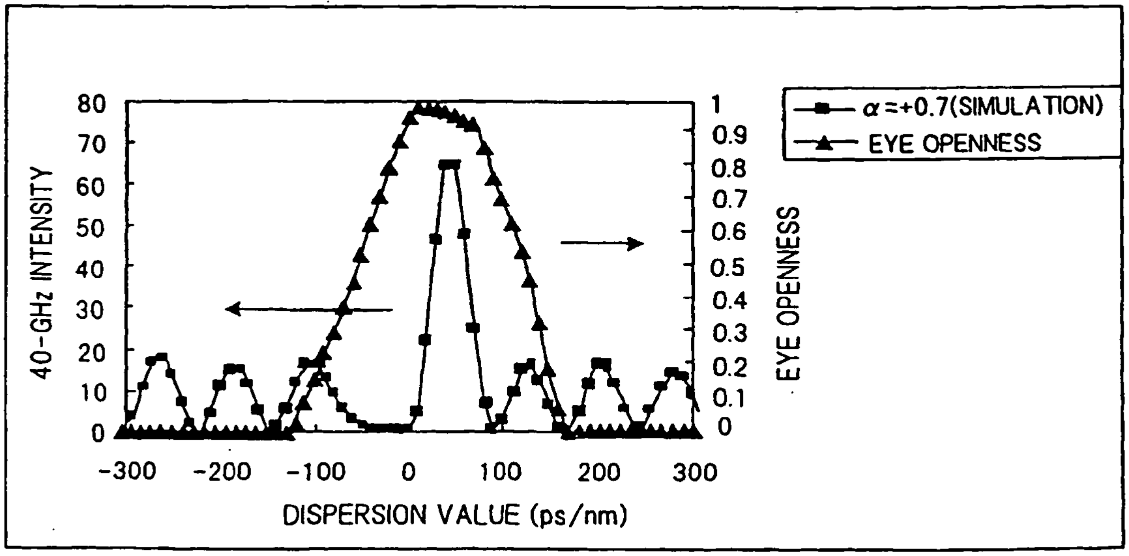


FIG. 77A

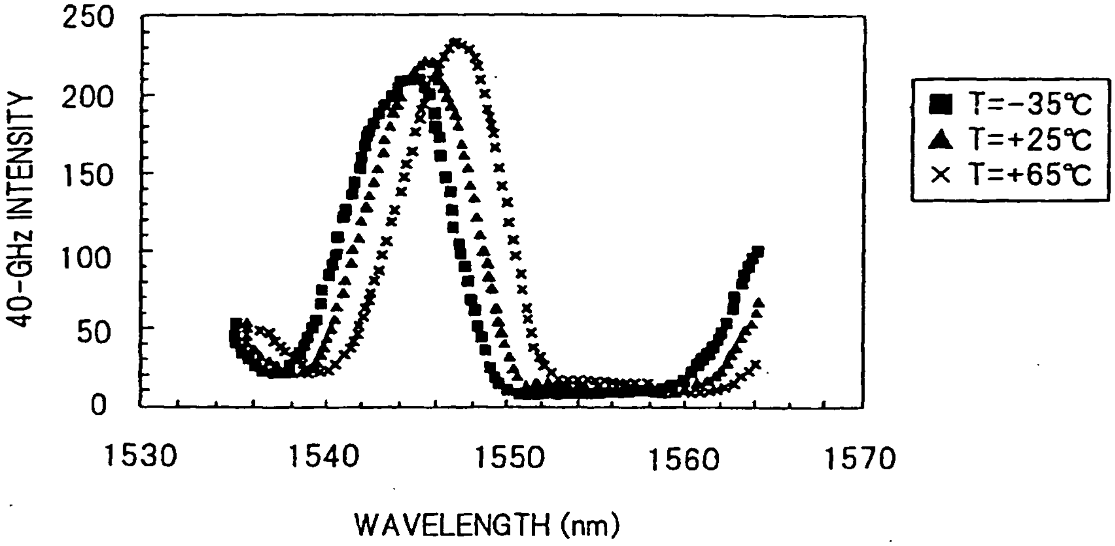
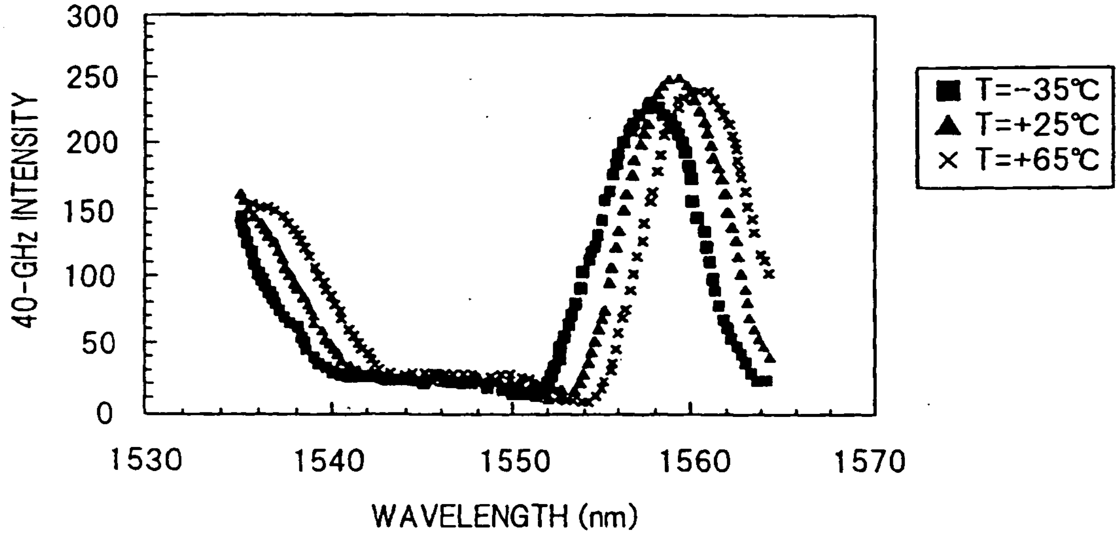


FIG. 77B



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